EMBER

The Electrotech Revolution

The shape of things to come

Daan Walter
Sam Butler-Sloss
Kingsmill Bond, CFA

September, 2025

The Age of Electrotech

Humanity is graduating from burning fossil commodities to harnessing manufactured technologies—from hunting scarce fossils to farming the inexhaustible sun, from consuming Earth's resources to merely borrowing them.

This isn't a marginal climate substitution. It's an energy revolution.

The magnetic centre is the electron: we are revolutionising how we generate, use, and connect electrons. Solar and wind are conquering electricity supply. EVs, heat pumps, and AI are electrifying major new uses. Batteries and digitalisation are connecting supply and demand.

Three reinforcing shifts. One energy revolution. The electrotech revolution.

At its core, this revolution is driven by physics, economics, and geopolitics. After all, the arc of energy history bends towards solutions that are leaner, cheaper and more secure.

Short-terms setbacks matter, but fundamentals matter more. And the fundamentals are stacked in electrotech's favour.

Physics. Electrotech makes a mockery of setting fossils on fire and losing two-thirds of the energy to heat. Electrotech is three times as efficient.

Economics. Technologies get cheaper with scale. Commodities get more expensive the deeper you dig.

Geopolitics. Three quarters of the world is dependent on fossil imports. 92% of countries have renewables potential over 10x their current demand.

Electrotech has grown exponentially for decades. The difference today is that it's too cheap to contain and too big to ignore. If current exponentials hold for five more years, global fossil demand will fall off its plateau.

Welcome to the Age of Electrotech.

Daan Walter, Sam Butler-Sloss, Kingsmill Bond

EMBER

Contents

EMBER

Chapter 1
A New Perspective: The Electrotech Revolution

01

Electrotech is a better way to explain reality

Most of the debate on the future of energy is between fossil gradualists and net zero advocates. We propose a third approach — the electrotech revolution — which better explains the extraordinary changes taking place in the energy system today.

02

Electrotech is electricity technology

Electrotech describes exponential energy technologies revolutionising how we generate, connect and use electrons – technologies enjoying learning curves and rapid growth, such as solar, wind, batteries, and digital solutions.

03

Electrotech releases 100x more energy

Electrotech enables us to harness the sun's enormous energy resources. The sun supplies Earth with as much energy every five days as all fossil fuel reserves combined. This makes possible a new energy era.

>> Return to Table of Contents

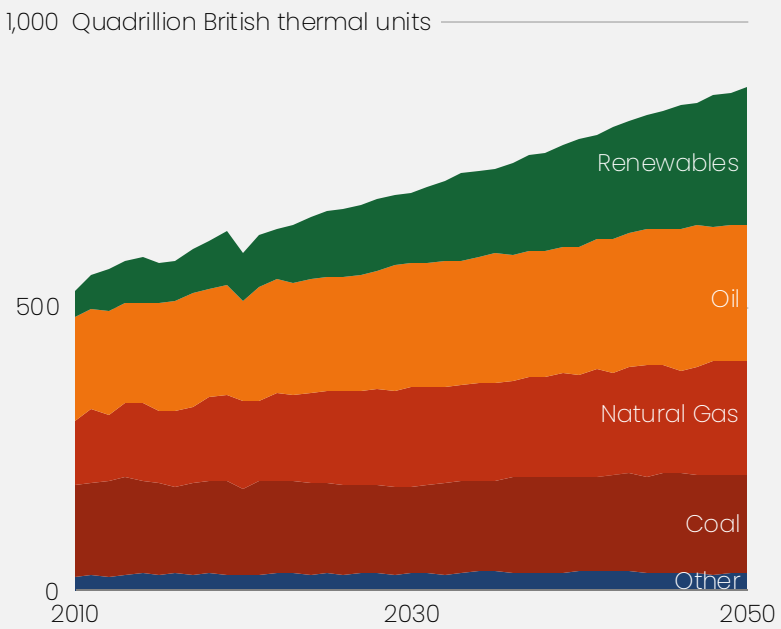
EMBER

Two views on energy dominate the conversation. We propose a third

The dominant energy views in the energy debate today

The incumbent energy view, centred on fossil fuels, slow change and business-as-usual

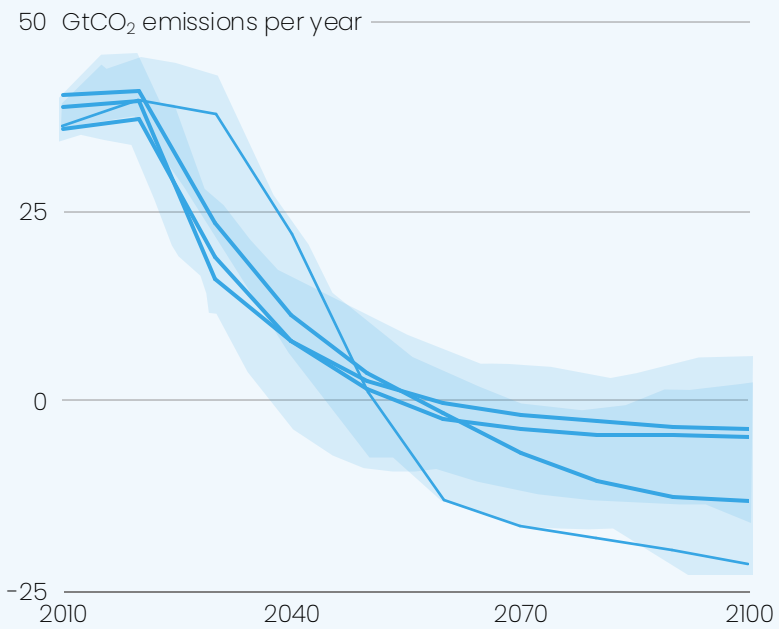
EIA – Primary energy supply



Source: Energy information Administration

The climate view, centred on emissions, policy targets and the moral obligation to fix climate change

IPCC – Pathways to net zero emissions

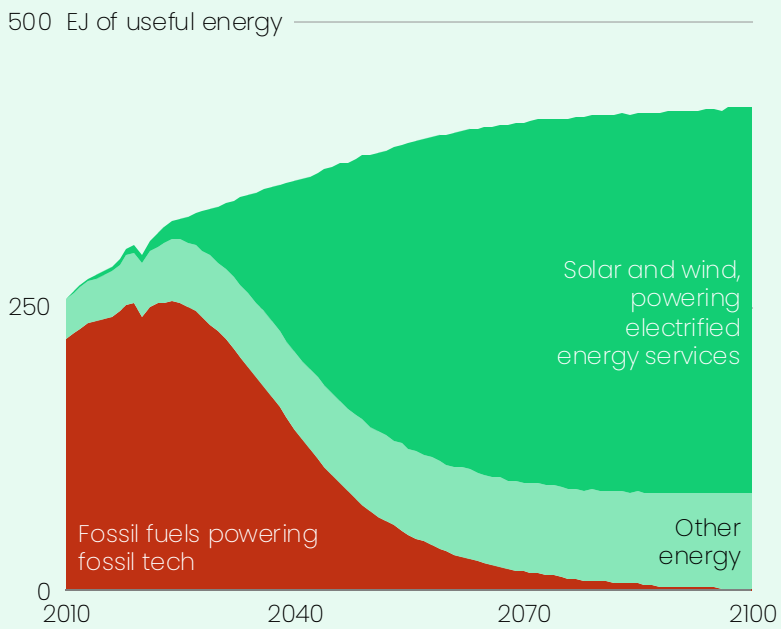


Source: Intergovernmental Panel on Climate Change (IPCC)

A third way: the electrotech view

The new electrotech view, centred on growth and innovation

Rystad – Global useful energy demand



Source: Rystad Energy

EMBER

This is a technology revolution in energy

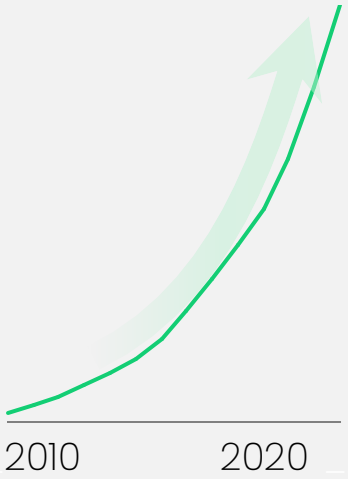
Electrotech is technology that revolutionises the supply, connection and demand of electricity

Supply

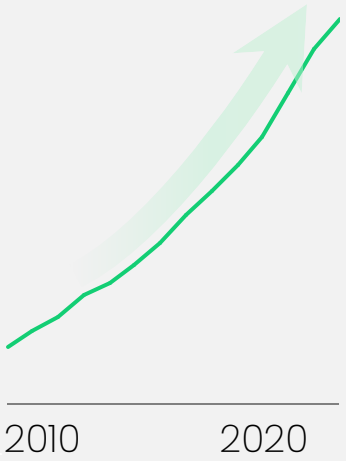
New ways to generate electricity

Renewables as vectors of change

Solar PV
deployment (GW)



Wind
deployment (GW)

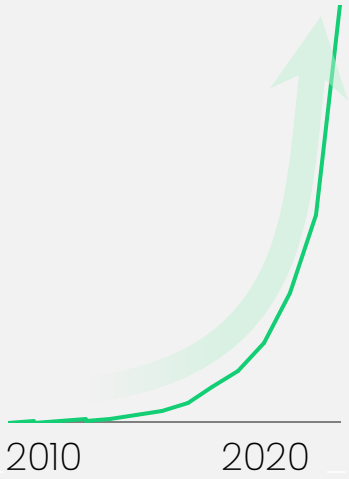


Connections

New ways to transport and store electricity

Flextech/gridtech as vectors of change

Battery storage
deployment



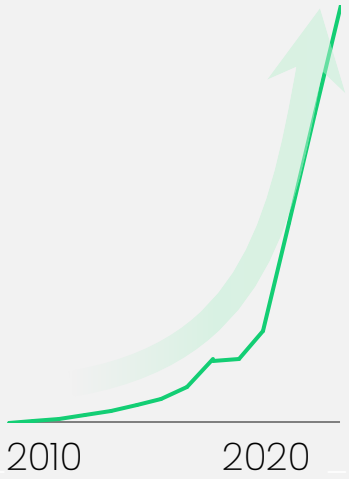
HVDC lines
deployment (km)

Demand

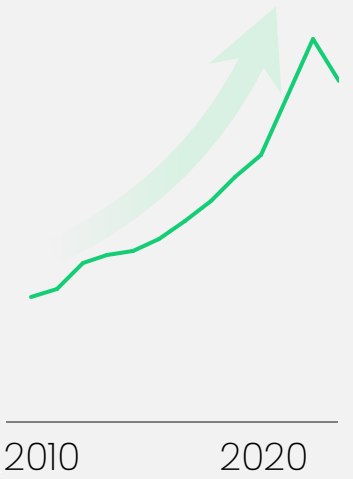
New ways to use electricity

Electrification as vector of change

EV
sales



Heat pumps
sales



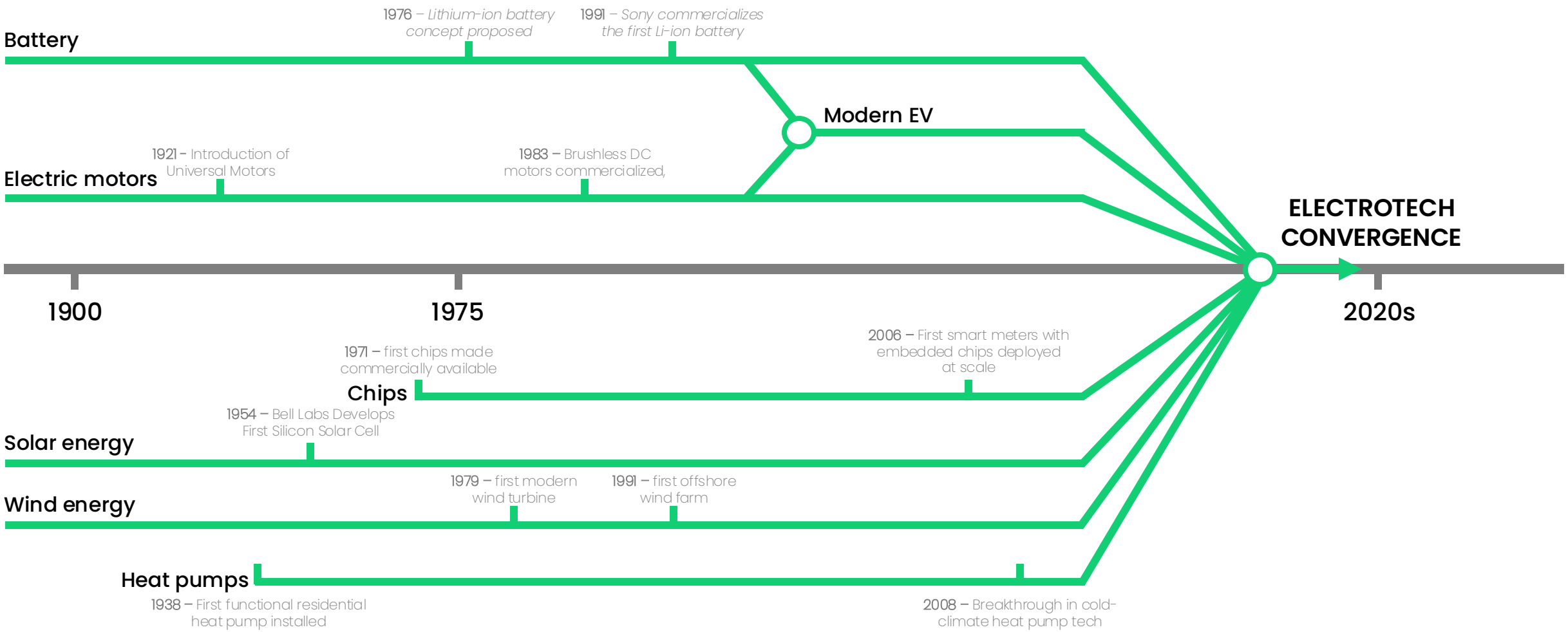
Sources: Ember, IEA, RMI, Thunder Said

EMBER

A century of evolution is converging into a decade of revolution

The 2020s mark a great technology convergence

ILLUSTRATIVE



Source: Ember

EMBER

This is the age of electrotech

It is the latest in a long line of technology shifts

Industrial Revolution
1st wave

Iron
Waterpower
Mechanisation

Age of steam and rail
2nd wave

Steam engines
Steam power
Rail

Age of steel and electricity
3rd wave

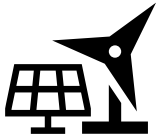
Electricity
Steel
Heavy engineering

Age of oil and mass production
4th wave

Mass-produced automobiles
Cheap oil
Petrochem

Digital Age
5th wave

Information technologies
Telecoms
Software



Electrotech Age
6th wave

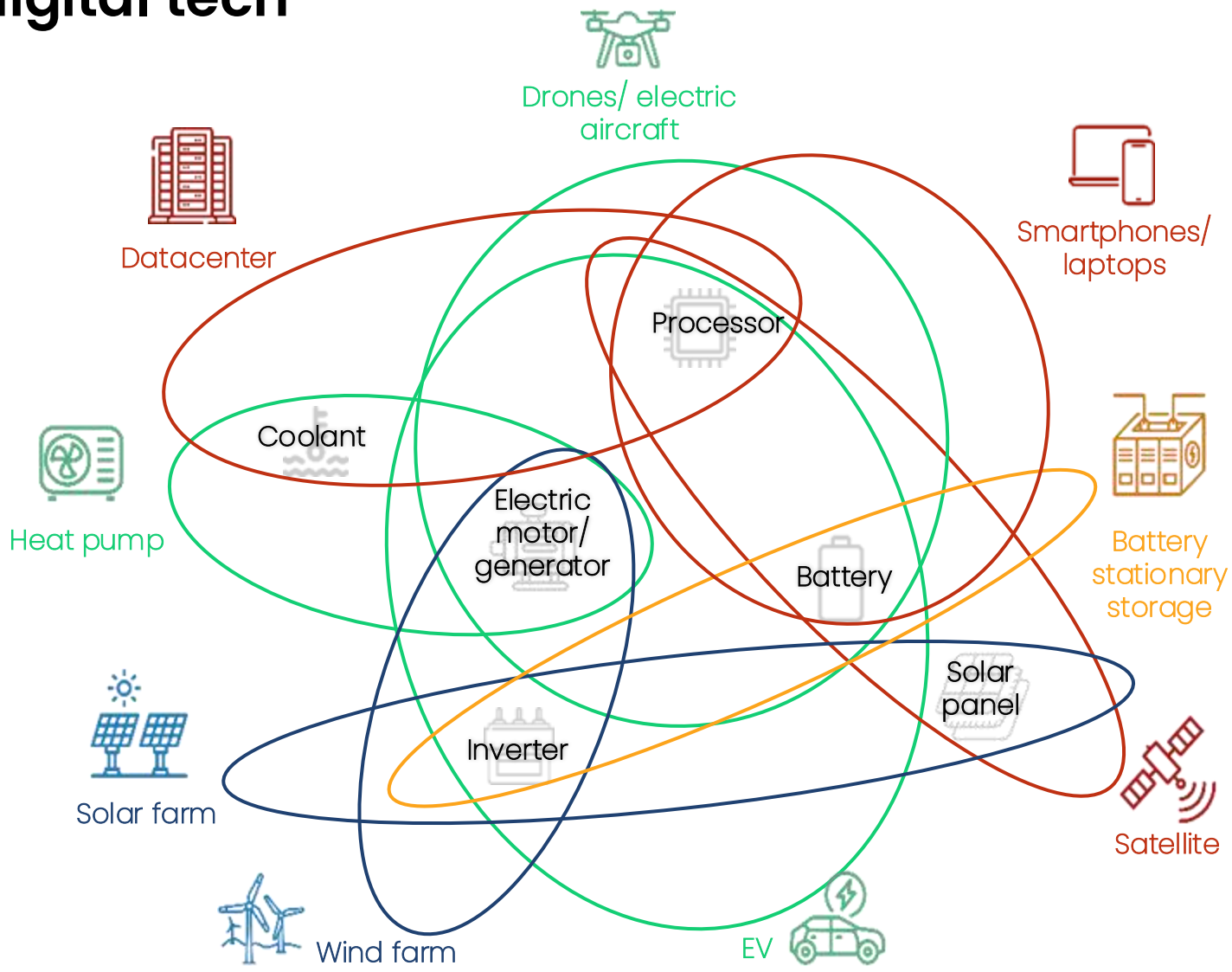
Renewable energy
Electrification
AI

Sources: Carlota Perez (first five waves), Ember Futures (6th wave)

EMBER

Electrotech is the child of digital tech

Electrotech is made of the same components as digital tech, and inherits its momentum

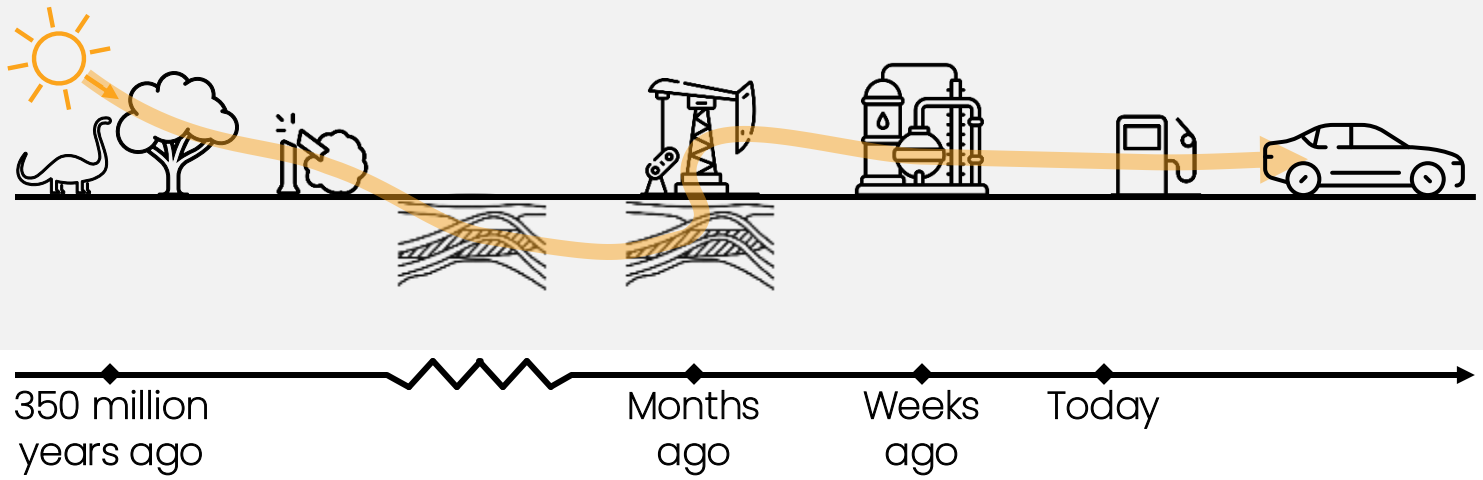


Source: Ember analysis

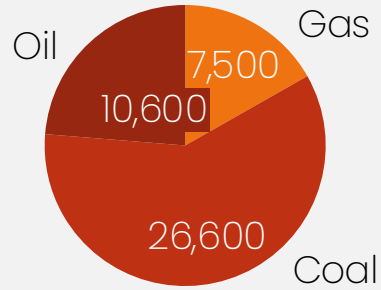
From burning old sunshine to using it real-time

The sun supplies more energy to Earth every 5 days than all fossil fuel reserves

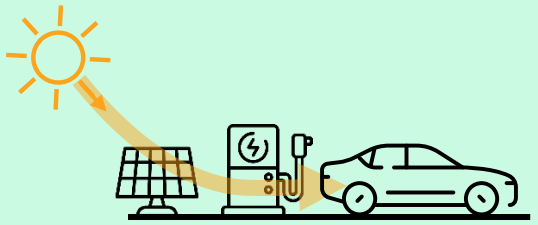
Fossil fuels



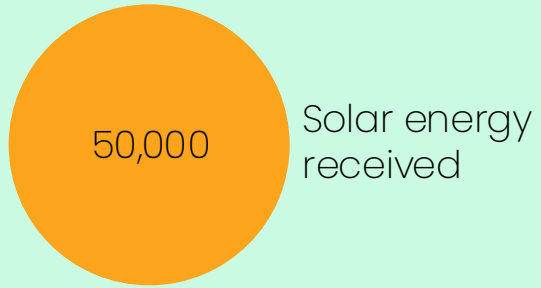
Total terrestrial energy reserves for the rest of time, current estimates, global, EJ



Electrotech – solar



Solar energy received from the sun every 5 days, EJ

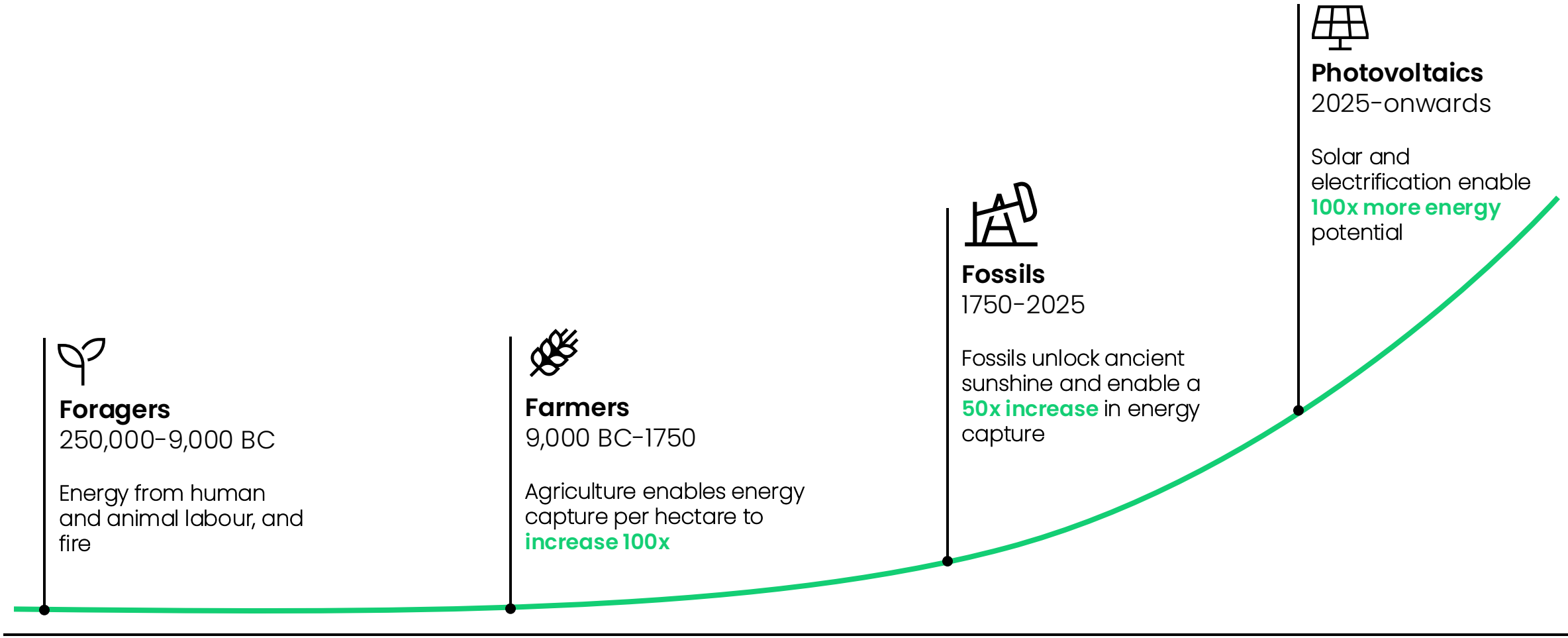


Sources: EI; Ember analysis. Note this is all solar energy received by the earth. We only need to extract a small fraction of it.

EMBER

Foragers, Farmers, Fossils, Photovoltaics

Electrotech enables another 100x leap in energy abundance



Sources: Ian Morris: Foragers, Farmers and Fossil fuels; Carbon Tracker: The Sky's the limit; Ember framing.

EMBER

Chapter 2
The rise of electrotech

01

Electrotech costs have fallen fast

Electrotech costs have been falling for decades on established learning curves of around 20% for every doubling in deployment. They now challenge fossil fuels on cost, with Dolphin EVs retailing in China below $10,000 and solar-plus-storage in India at $40 per MWh. As a result, capital is shifting, and two-thirds of energy expenditure is going into electrotech.

02

Growth has been exponential

Key electrotech technologies have enjoyed exponential growth. We see this for generation (solar and wind), connections (batteries and software) and usage (EV and heat pumps). Change is led by China, and is now cascading into the emerging markets. ASEAN, for example, leapfrogged the US in electrification in 2023.

03

The ceiling of the possible is high above us

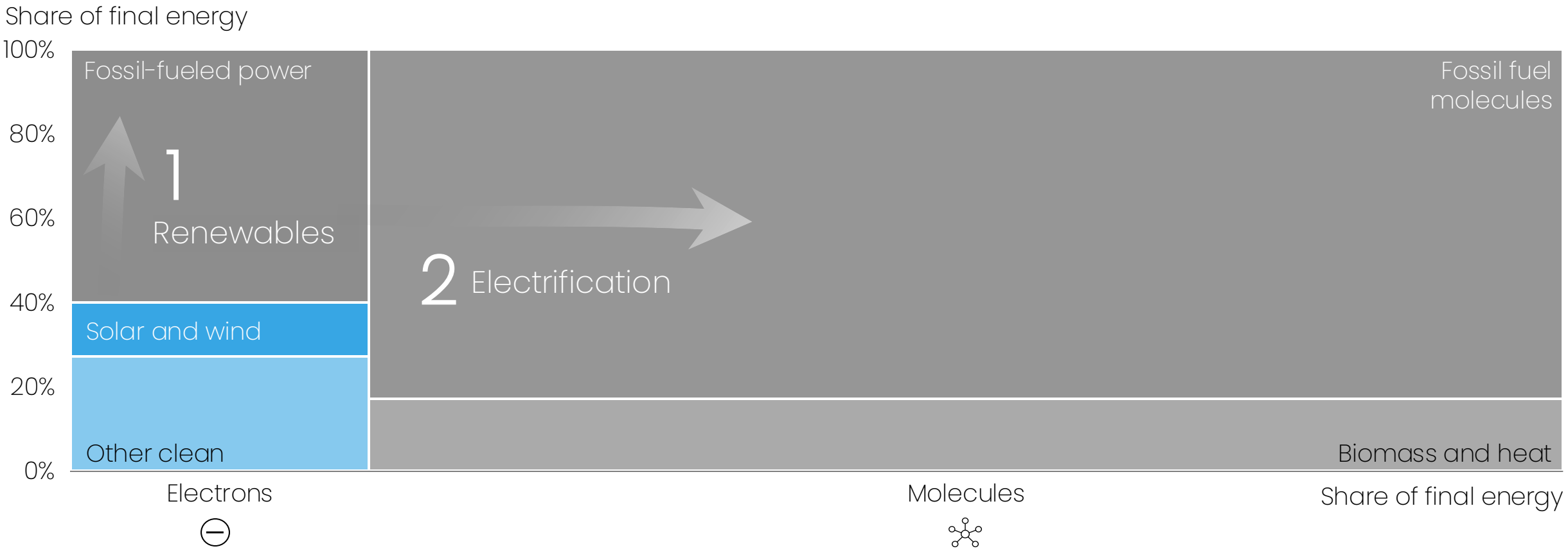
We already know how to get solar and wind to 70-80% of generation at a cost comparable with fossil fuels and how to electrify around 75% of end demand. So we can more than triple renewables and electrification.

>> Return to Table of Contents

The two vectors of the energy transition

Renewables replace fossil electricity; electrification replaces fossil molecules

Global final energy demand in 2023



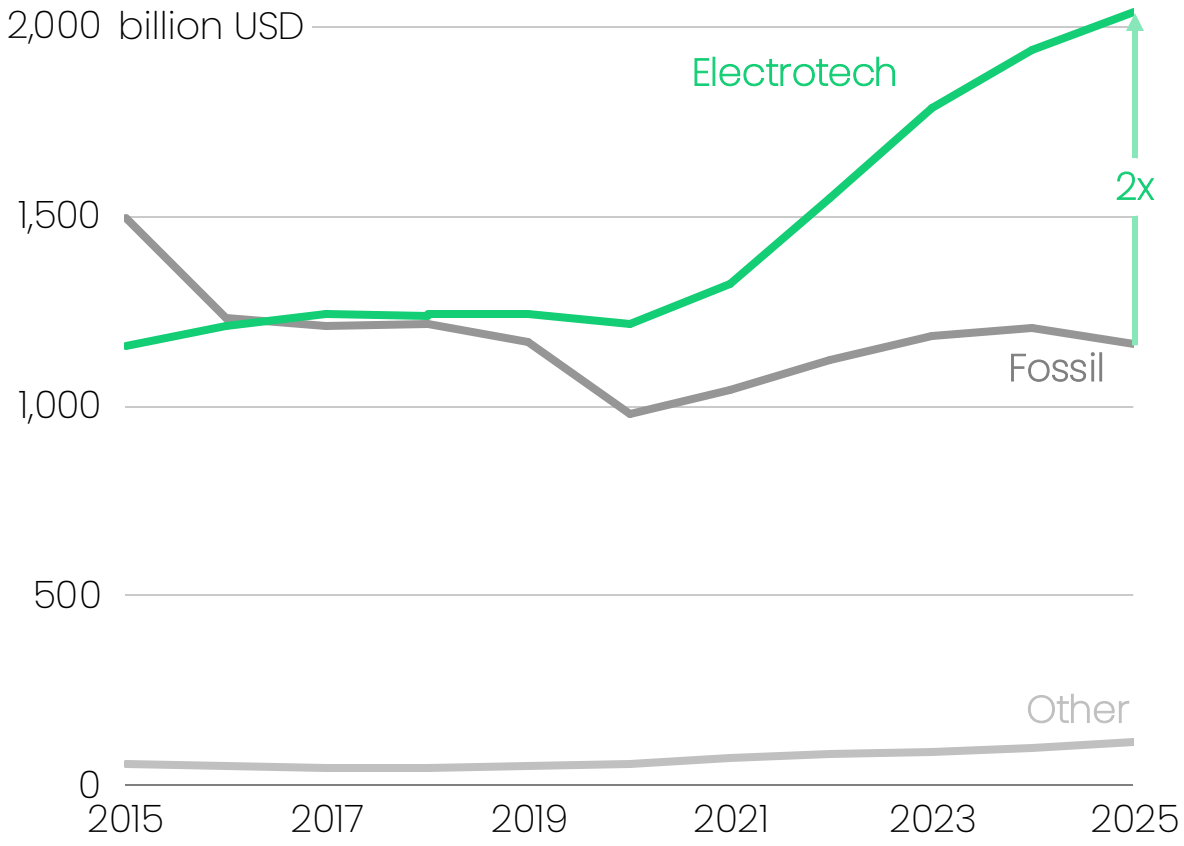
Sources: IEA WEO 2024; Ember analysis. Other clean electrons are mainly nuclear and hydro.

EMBER

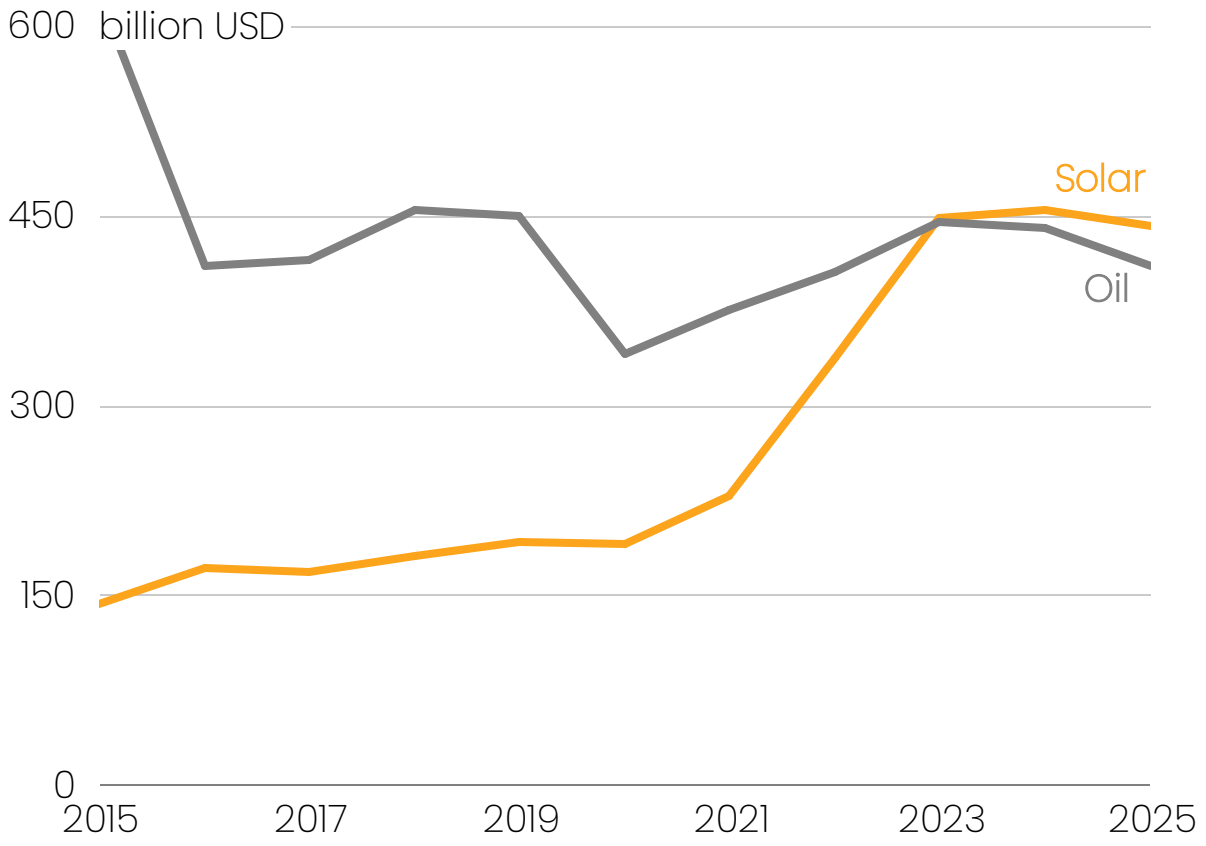
Electrotech investment is twice as big as fossils

And we spend more on solar capex than on oil

Energy investment by category



Solar and oil investment



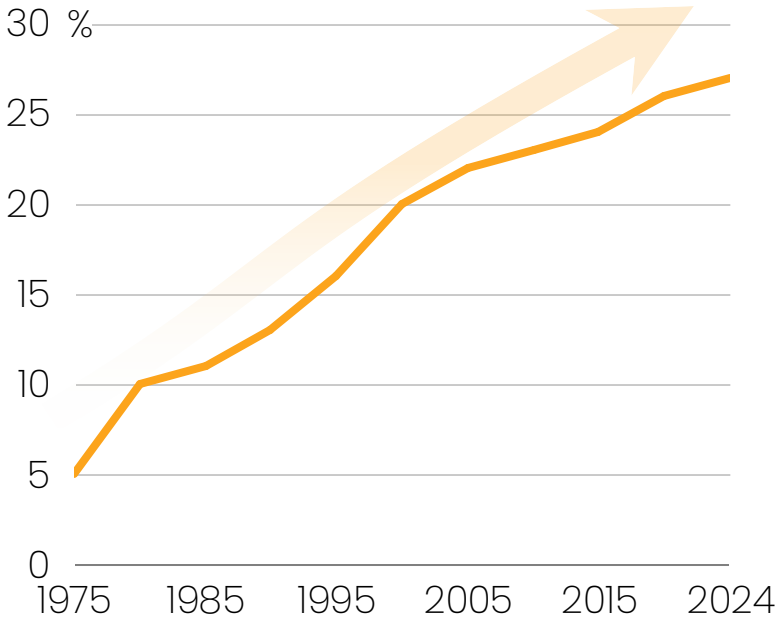
Sources: IEA WEI, Ember analysis – Note: Oil investment on the right hand side is upstream investment

EMBER

Electrotech keeps getting better

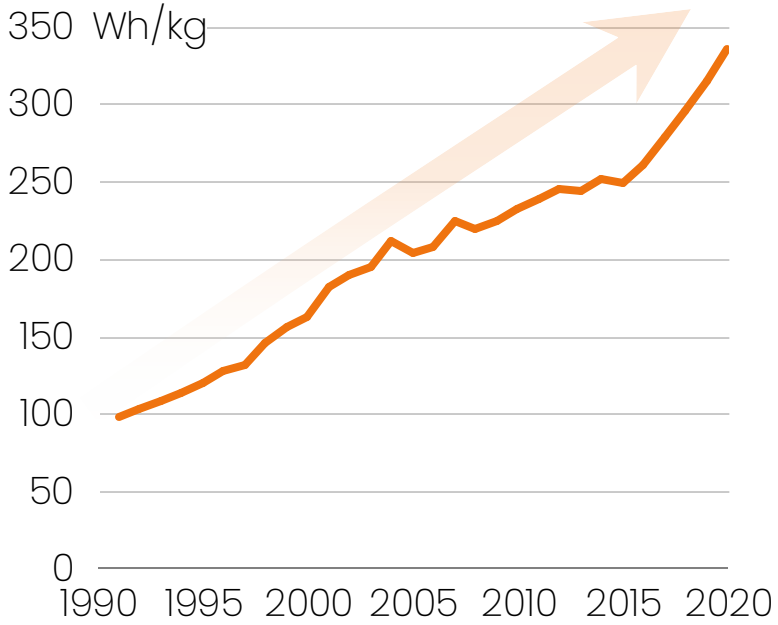
Decade after decade of innovation raises the ceiling of the possible

Solar cell efficiency



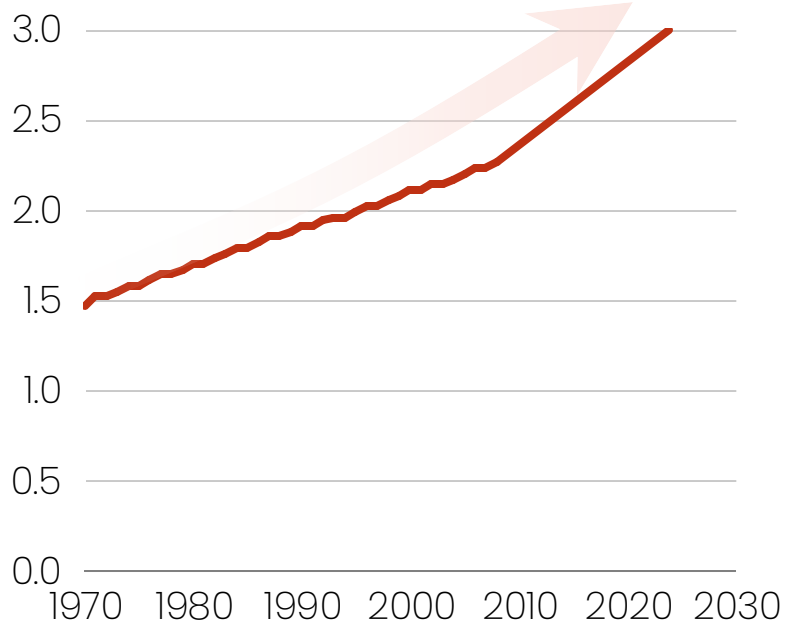
More efficient solar cells mean more space and material efficiency and lower cost

Top-tier battery cell density



Denser batteries mean longer EV ranges; new EV applications opening up and more material efficiency

Heat pump coefficient of performance, US sales average



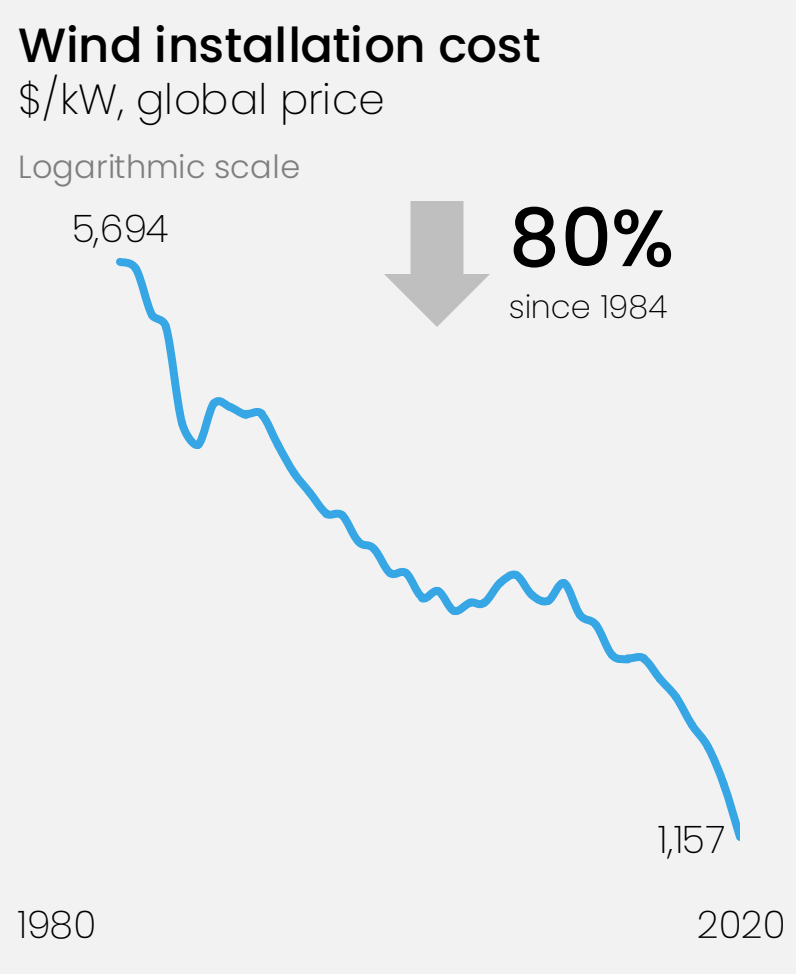
Higher COP means a more efficient and powerful heating system

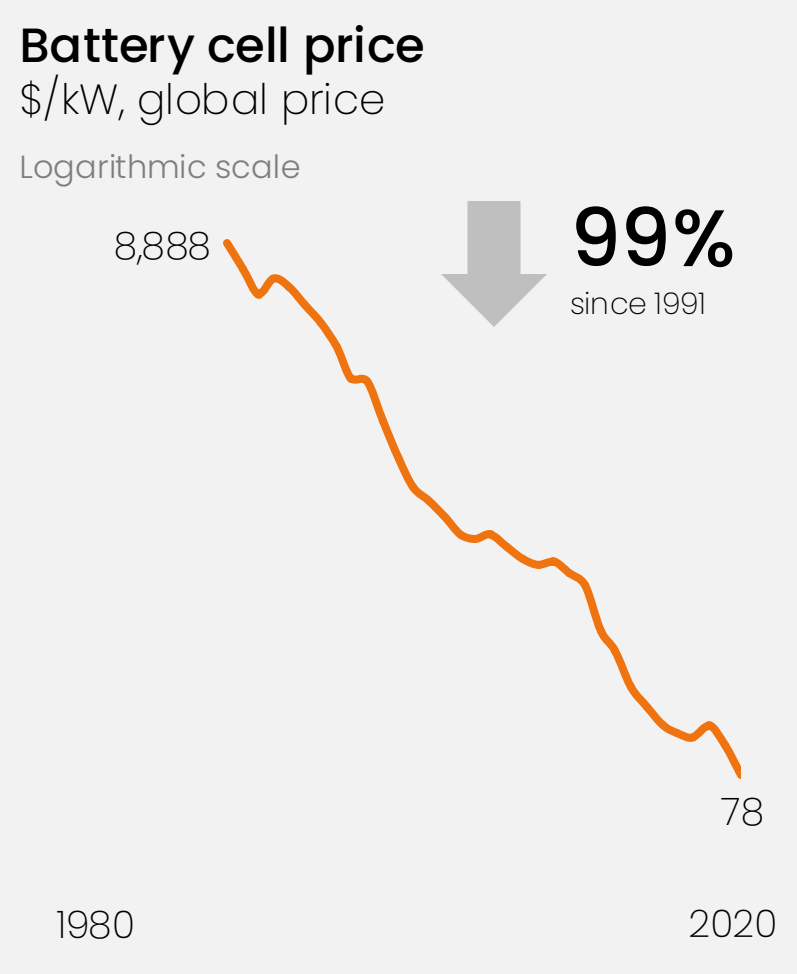
Sources: RMI X-Change Batteries, US DOE, US NREL; Ember analysis

EMBER

Costs have been falling for decades on learning curves

Decades of steady cost innovation improved electrotech economics

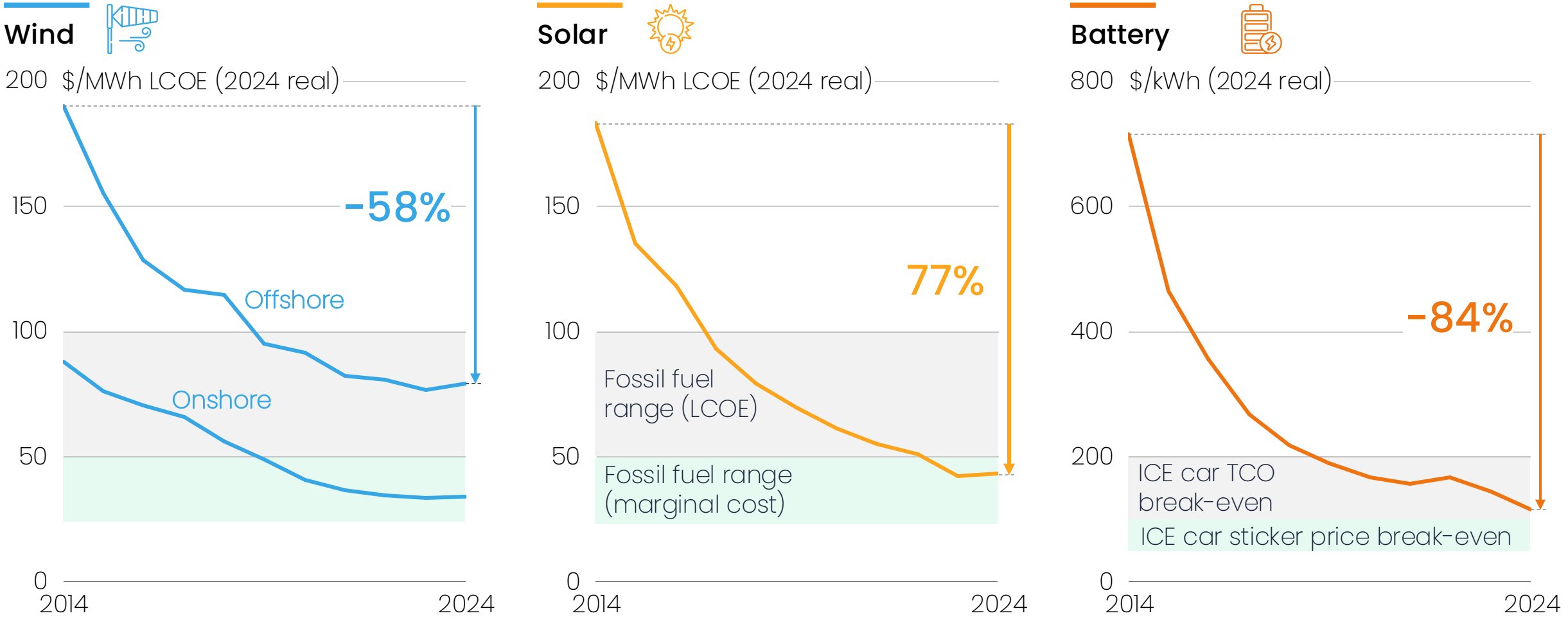




Sources: OWID; IRENA; BNEF/Avicenne

Cheap enough to challenge incumbents

After decades of cost innovation electrotech is now cheaper than fossils



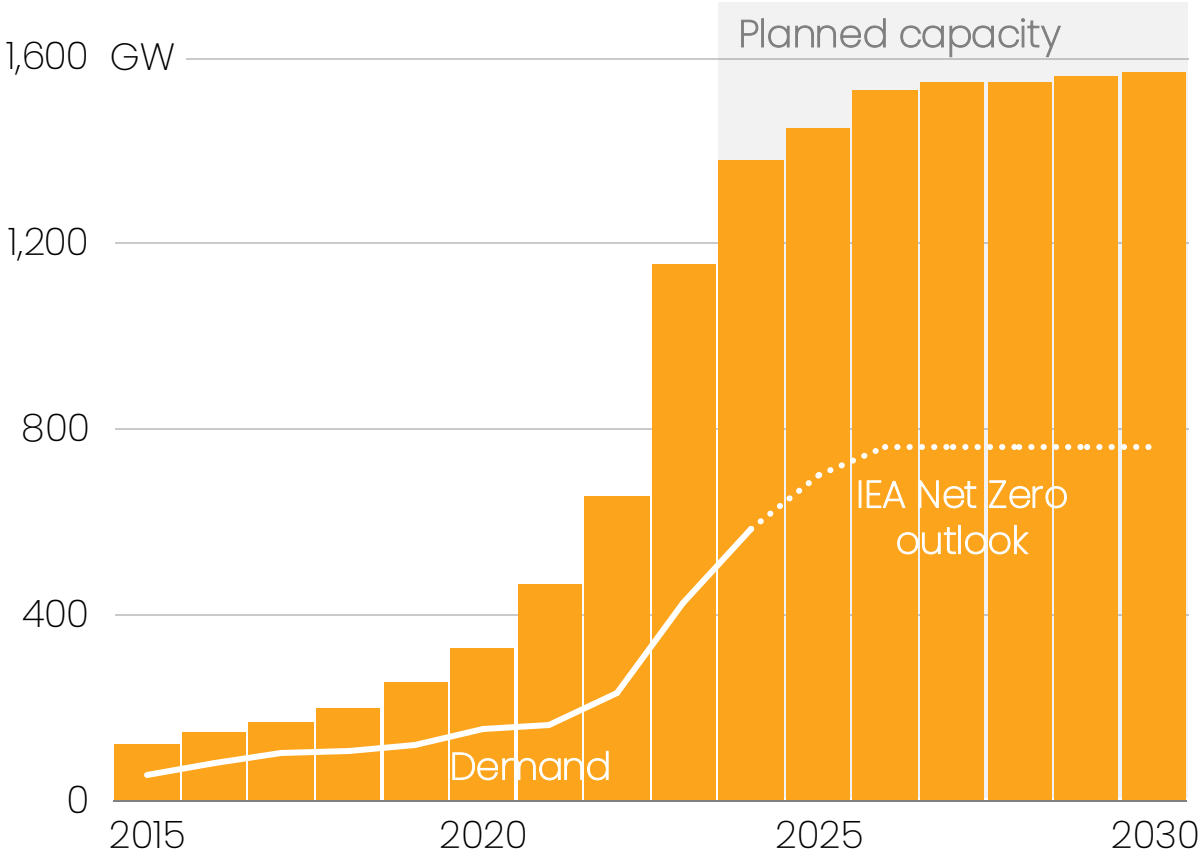
Sources: IRENA, BNEF (Batteries), Ember

EMBER

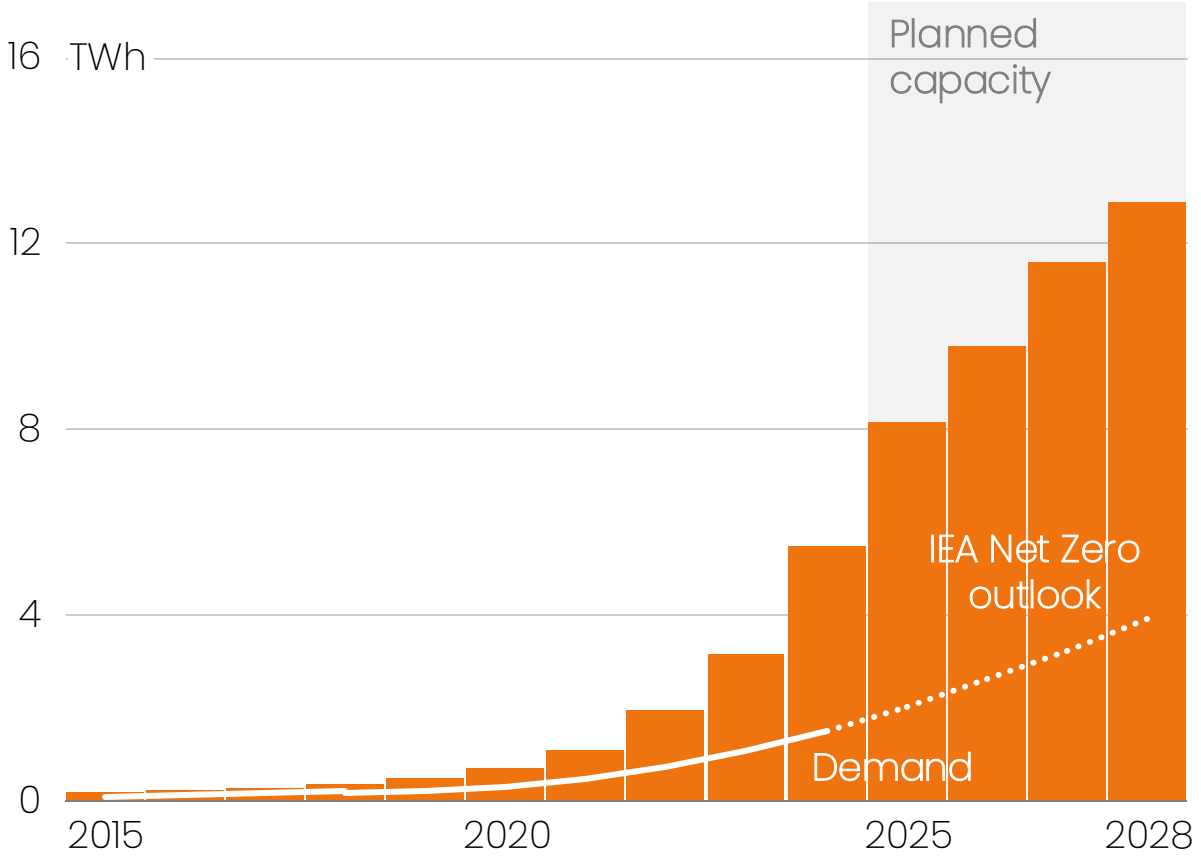
The manufacturing capacity is in place

Outpacing projected demand of even net zero scenarios

Solar PV manufacturing capacity



Battery manufacturing capacity



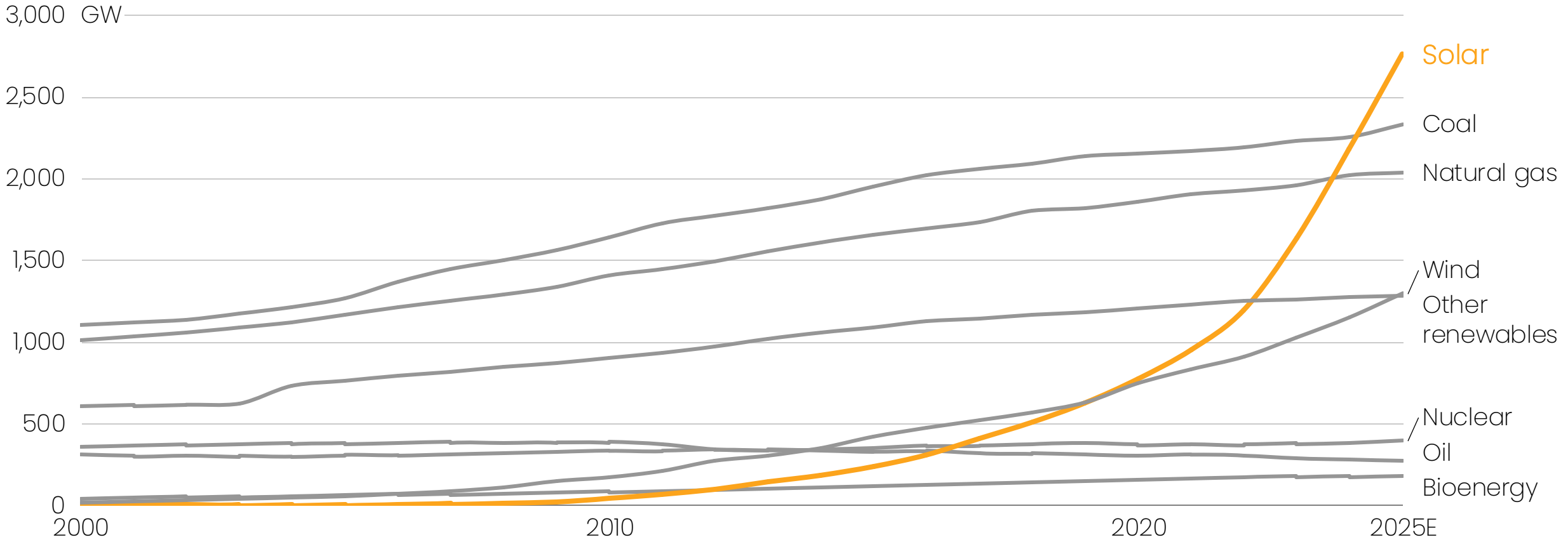
Sources: IEA; Ember analysis. The IEA net zero outlook is chosen as an illustration that capacity is above even this level.

EMBER

Sunrise

Solar has gone from smallest to largest source of capacity in 15 years

Global installed electricity capacity

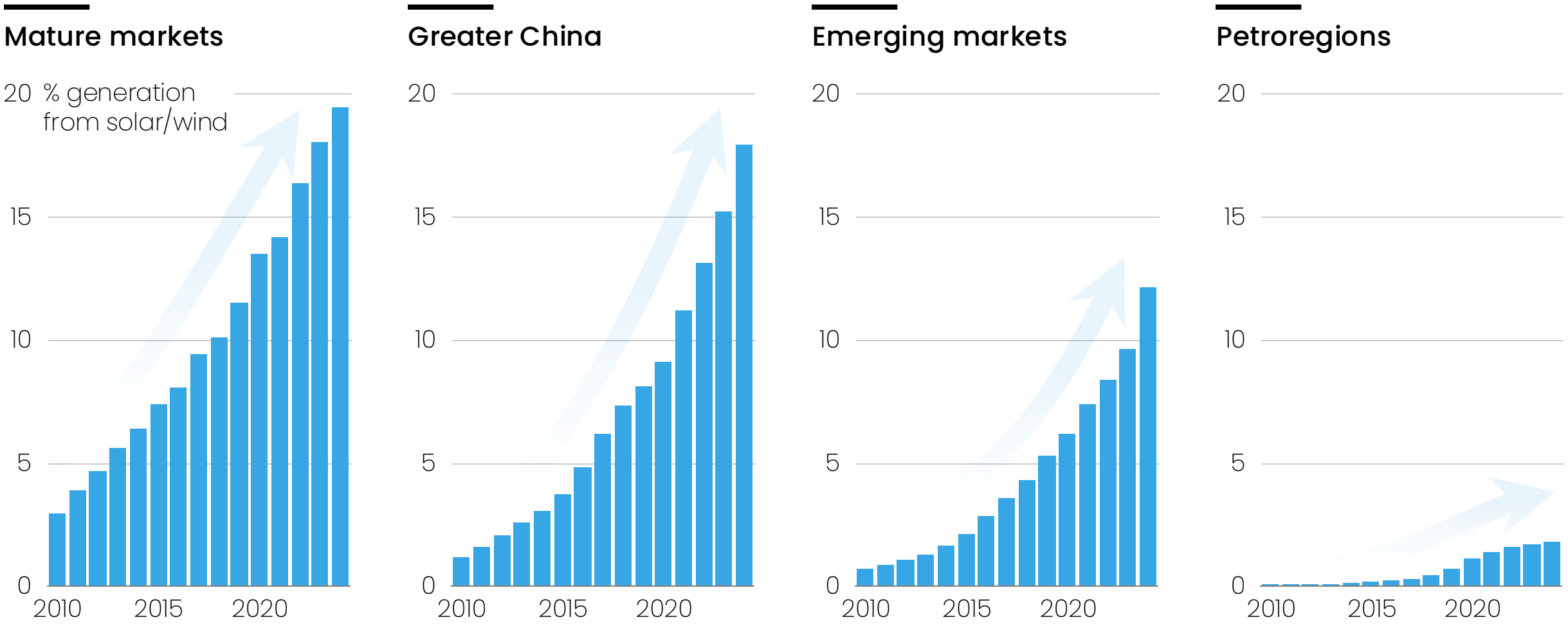


Sources: BNEF

EMBER

Solar and wind deployment is a global story

From mature economies to emerging markets



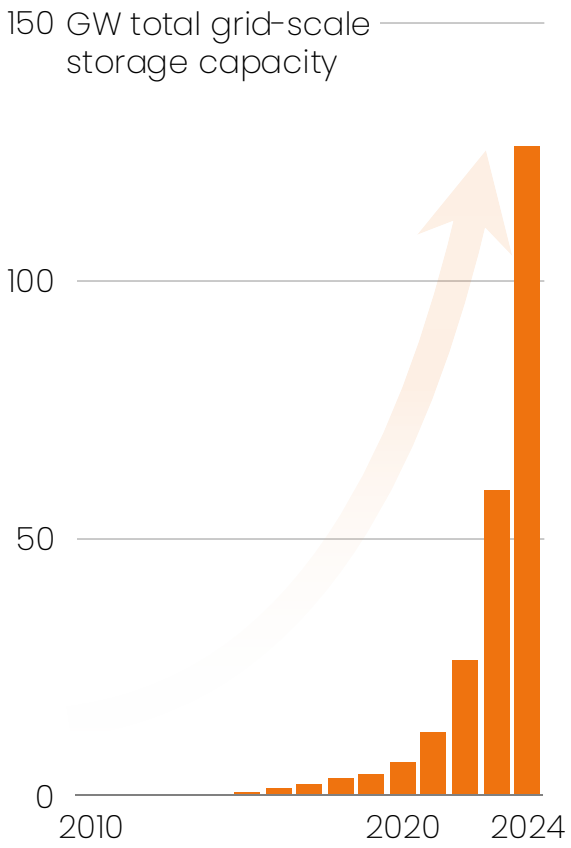
Sources: Ember. Note: Emerging markets include Latin America, Africa, South Asia and Southeast Asia; Petroregions include the Middle East and Eurasia.

EMBER

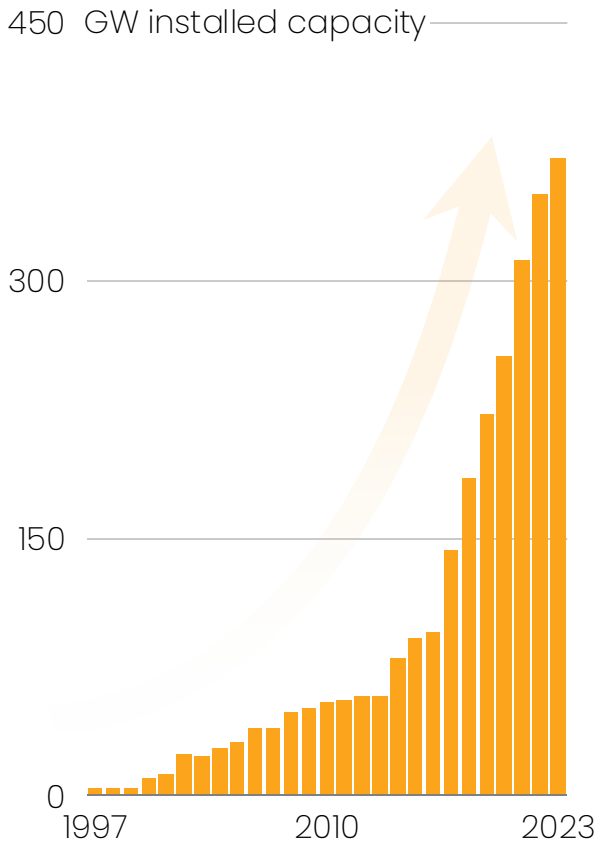
The rise of new connections

Flextech and gridtech smartly connect supply and demand

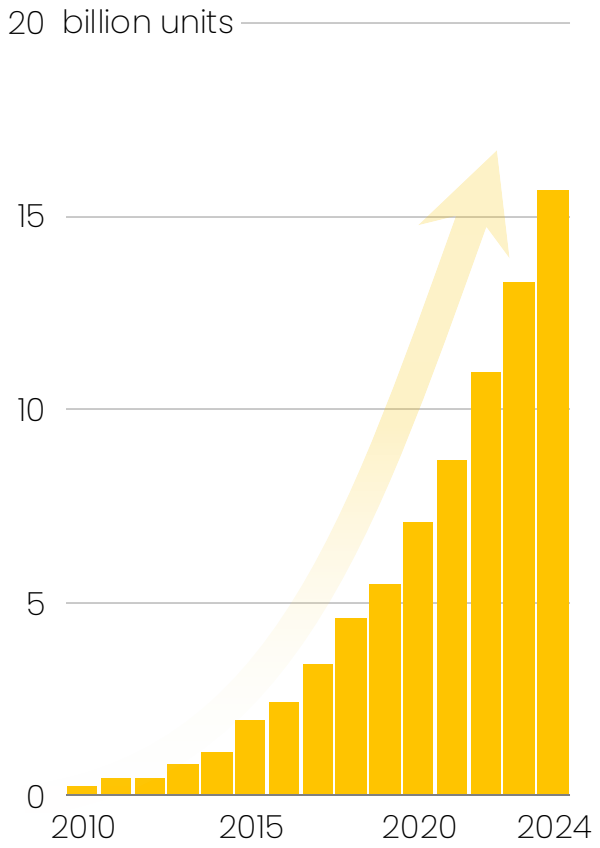
Battery storage capacity



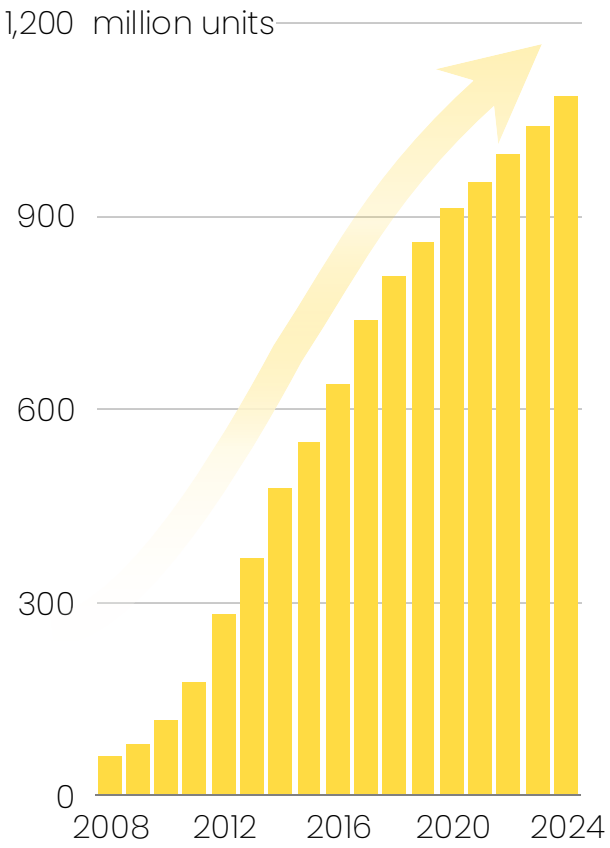
High voltage DC transmission



Internet connected devices



Smart meters installed



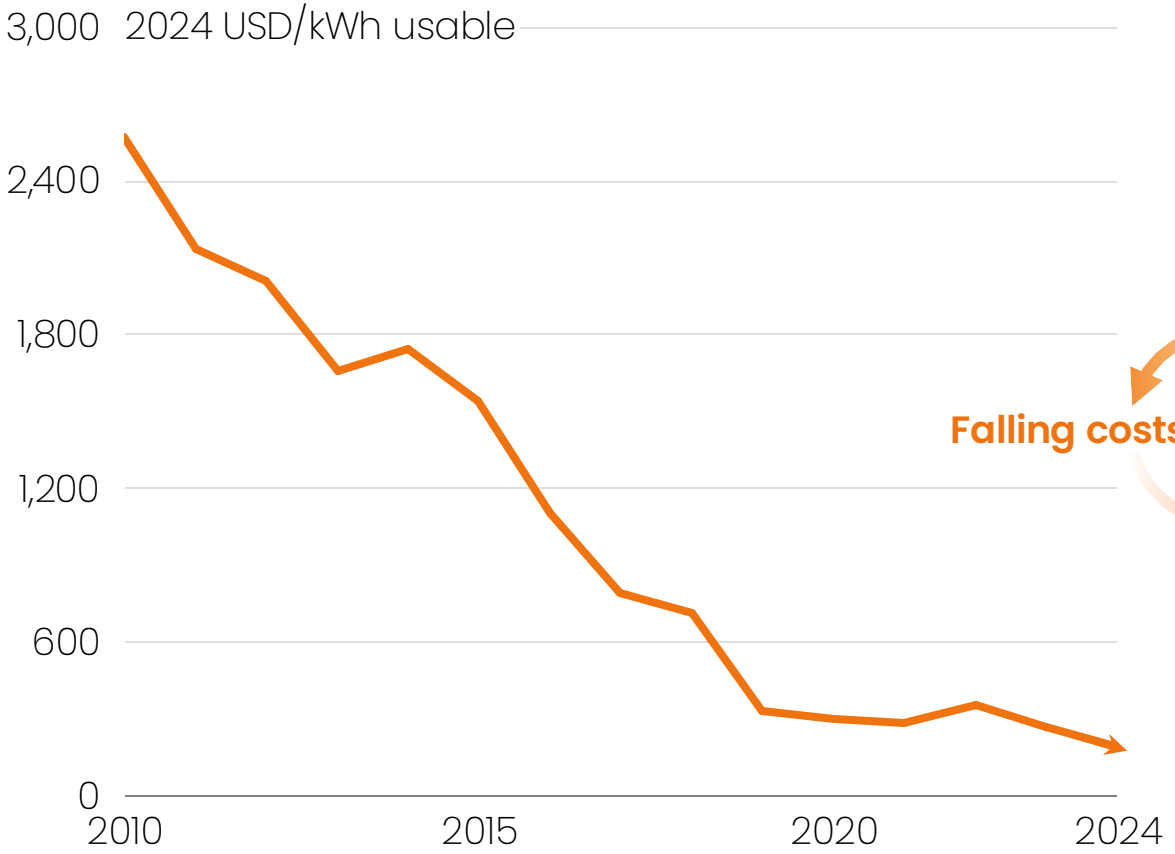
Sources: Energy Institute, IEA; Thunder Said; Ember analysis

EMBER

The cheaper it gets, the faster it goes

The virtuous cycle between cost and volume is self-sustaining

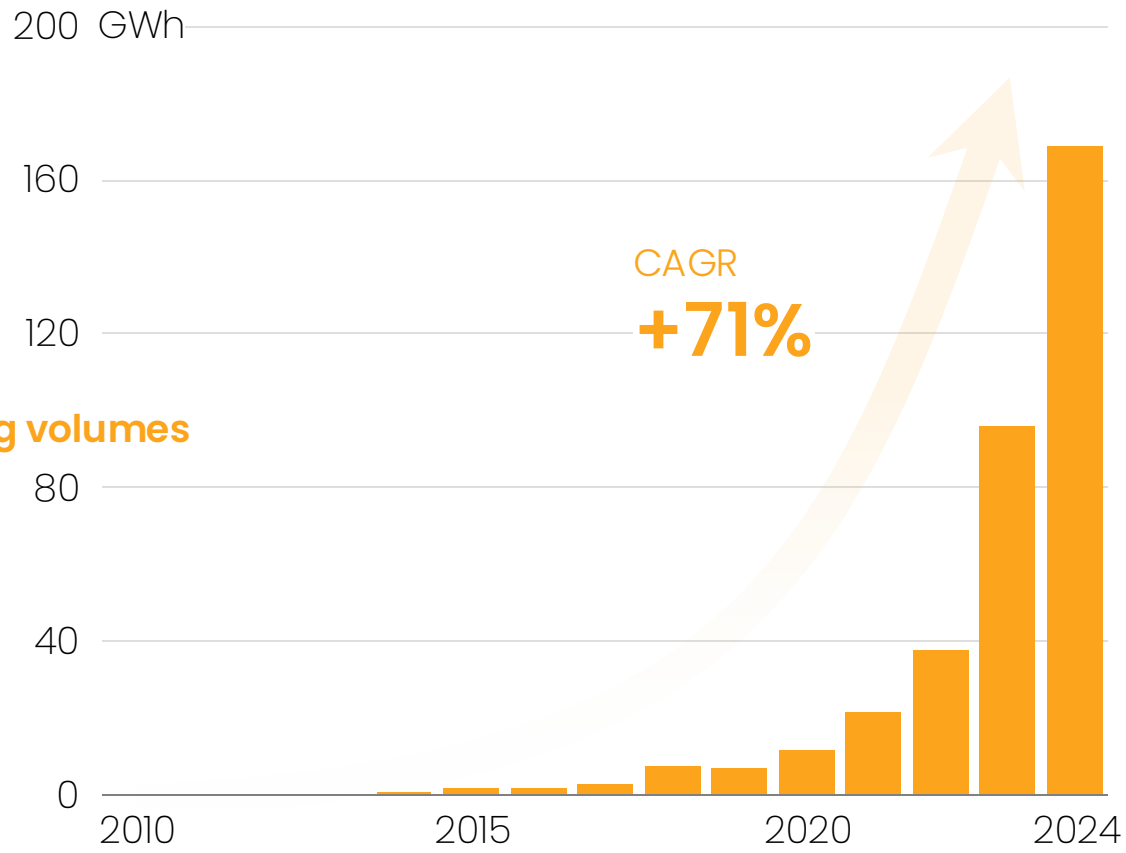
Utility-scale energy storage cost, global



Falling costs

Rising volumes

Utility-scale energy storage sales, global

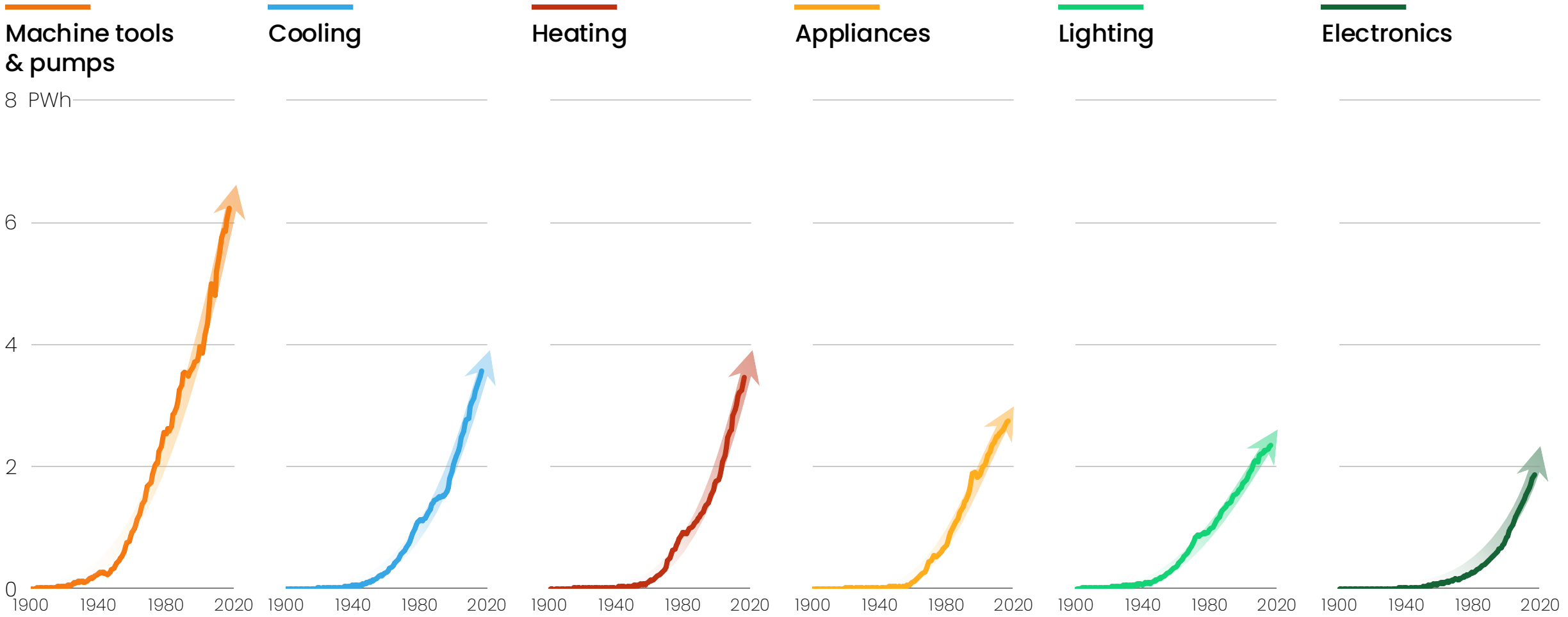


Sources: IRENA, Ember

EMBER

The long march of electrification

We've been electrifying the global economy for over a century

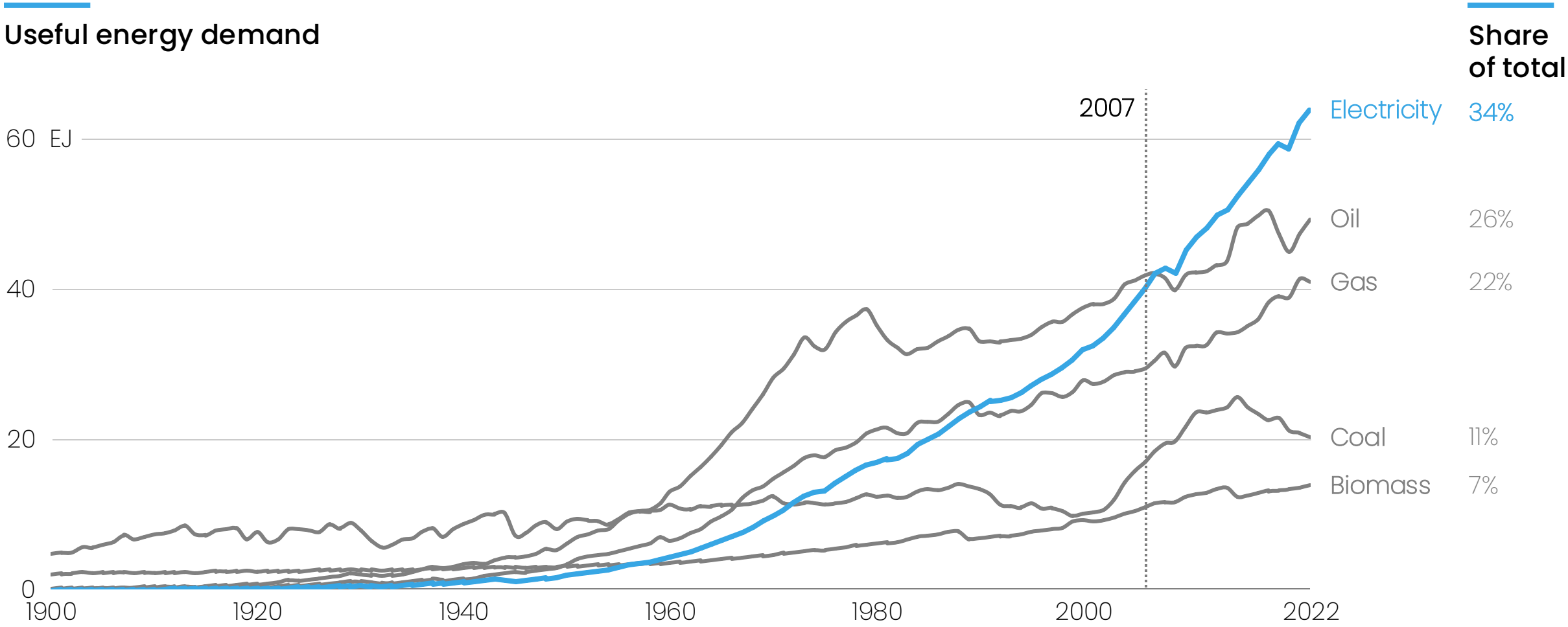


Sources: Pinto et al, 2023; Ember analysis. Electricity consumption by end-uses.

EMBER

Electricity is the king of energy

Electricity overtook oil as largest supplier of useful energy in 2007

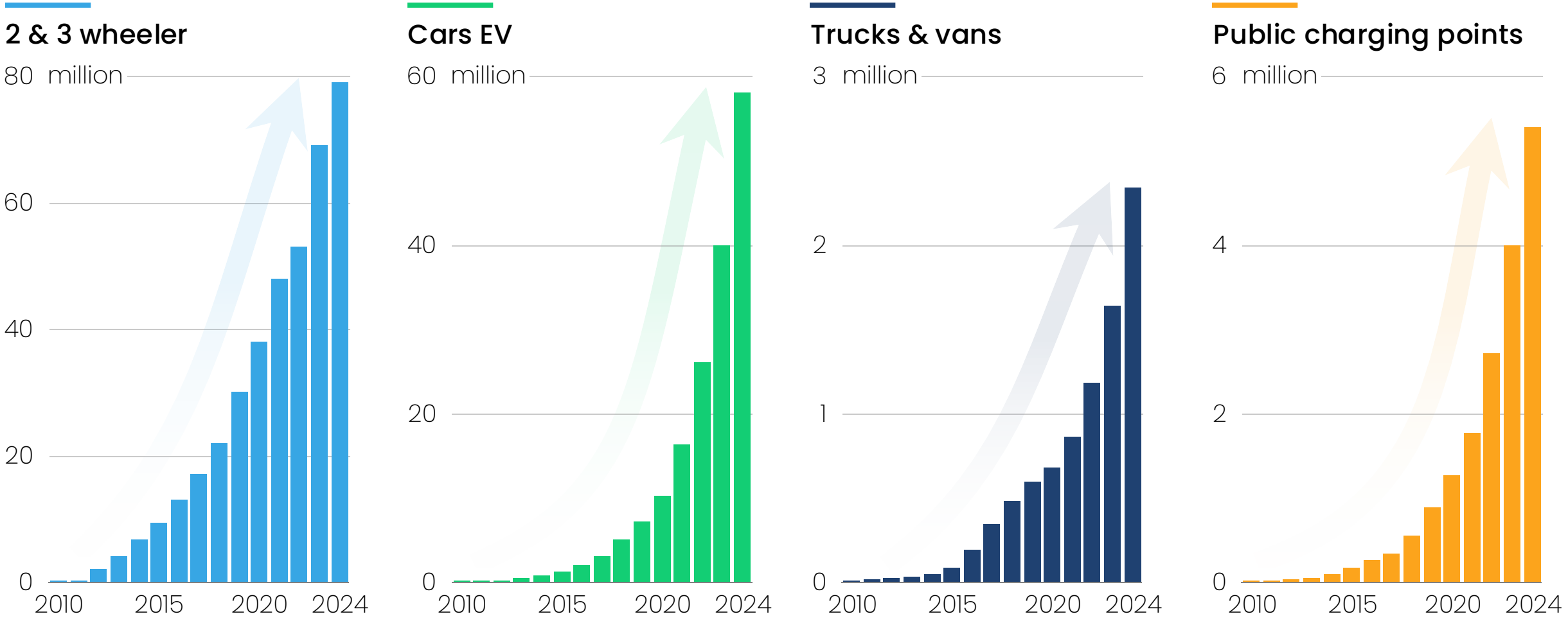


Sources: IIASA, IEA, Ember analysis. All figures exclude feedstock use. Useful energy demand refers to the amount of energy used to perform a specific task, after accounting for energy losses in the process

EMBER

The EV revolution is taking off

Electric mobility is growing exponentially across vehicle sizes

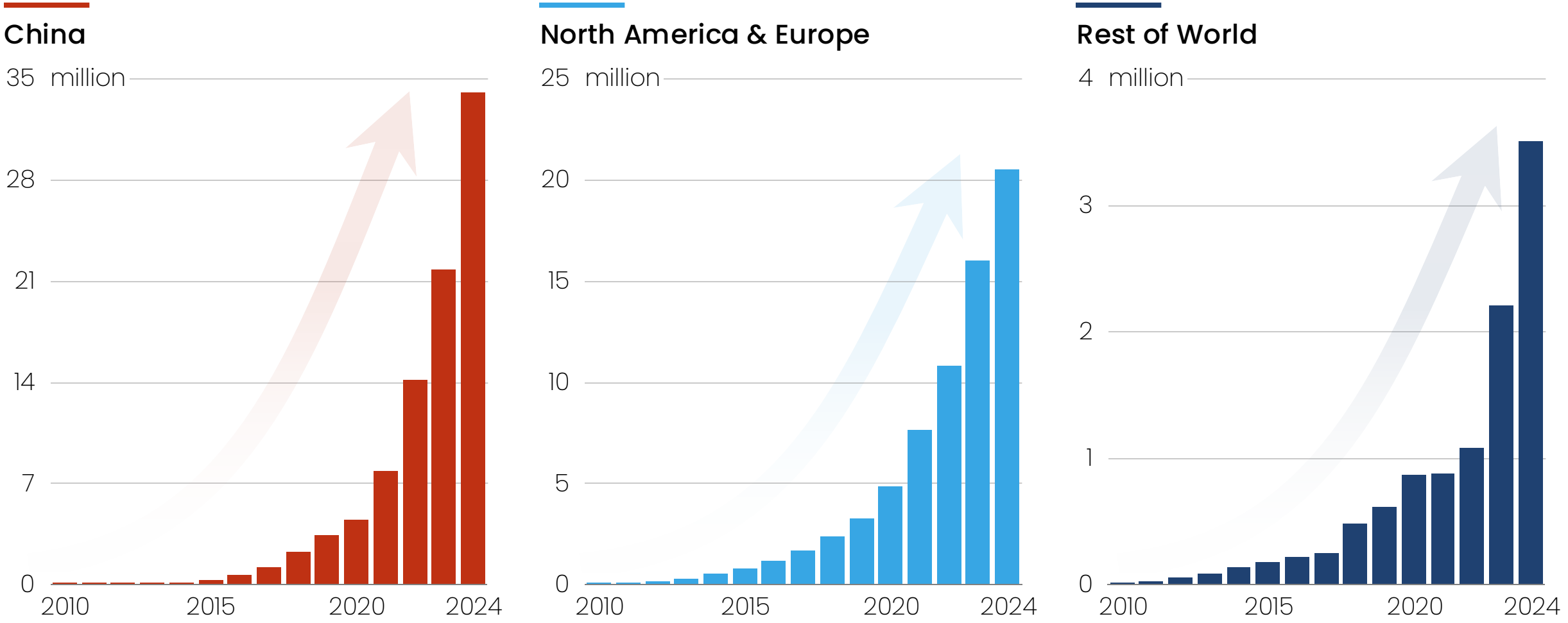


Sources: IEA. Note these figures are for the size of the fleet

EMBER

EV deployment is growing exponentially

Double digit growth across the world



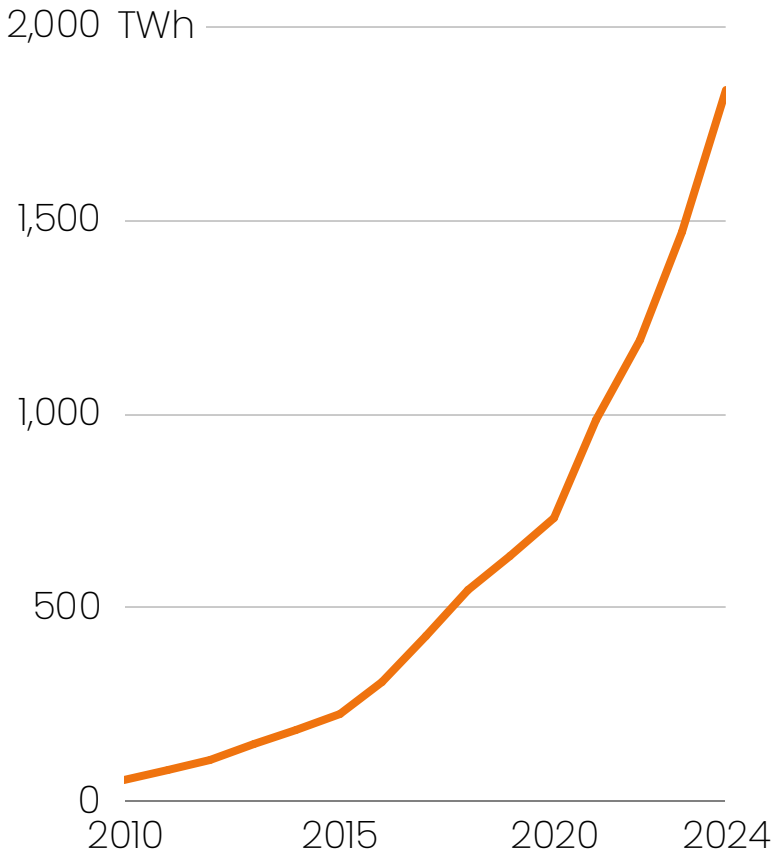
Sources: IEA, Ember analysis – Note: showing total fleet numbers for cars

EMBER

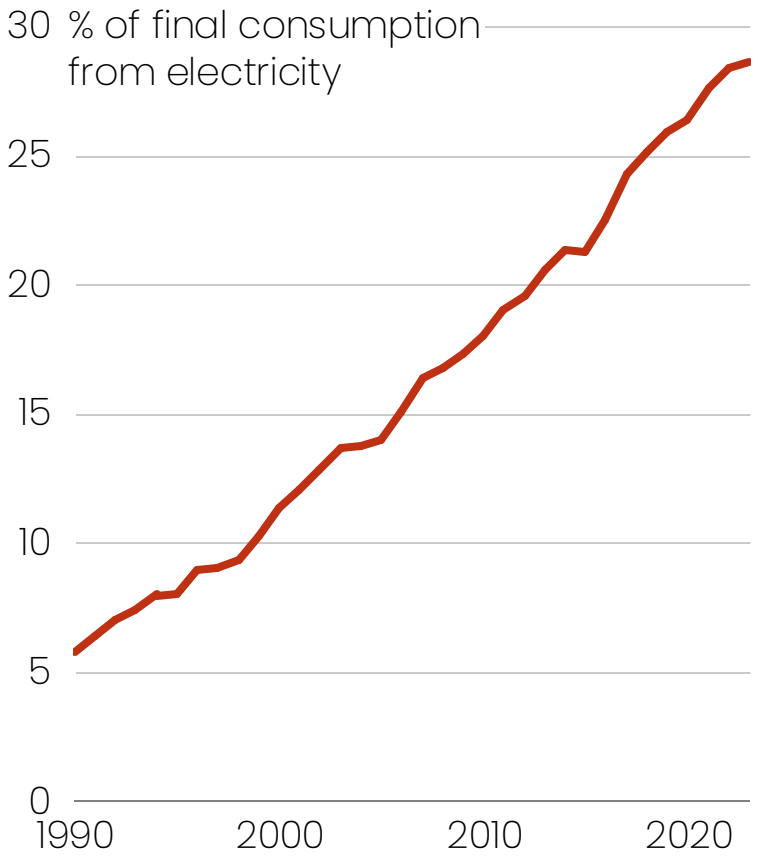
China is moving at lightning speed

Across renewables and electrification

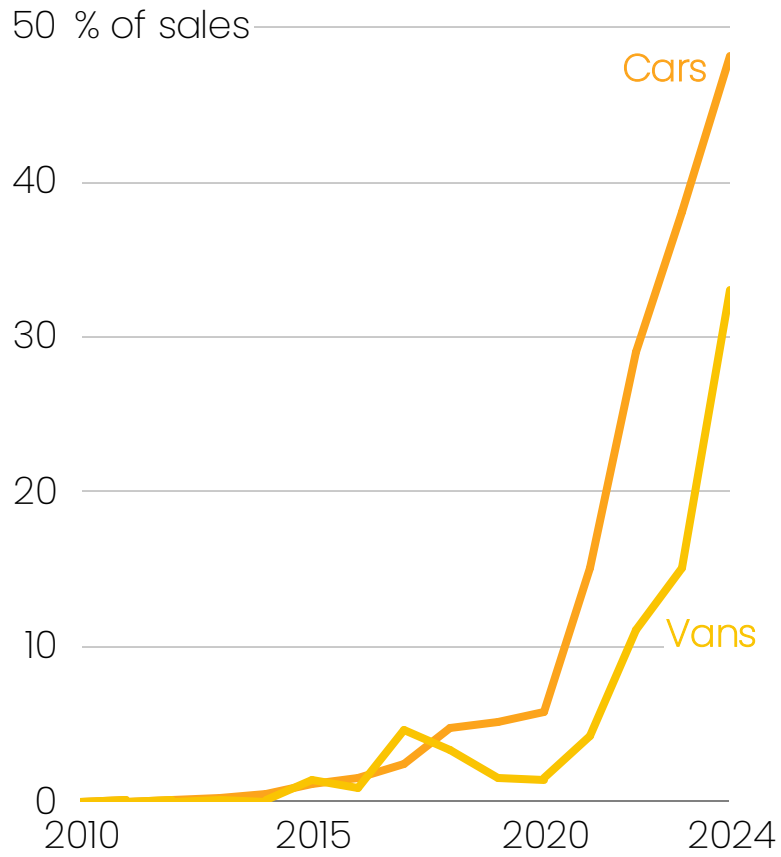
Solar and wind generation



Electrification



Electric vehicles



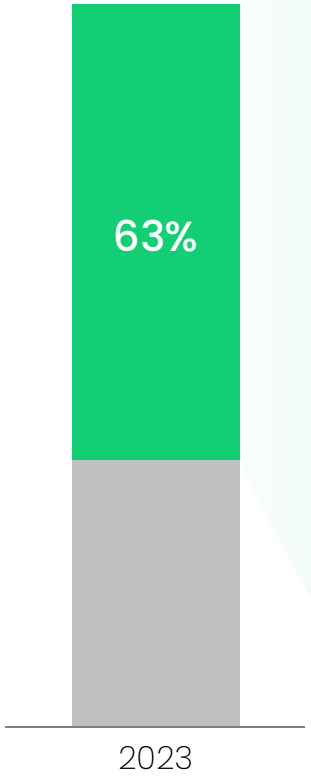
Sources: Ember, IEA

EMBER

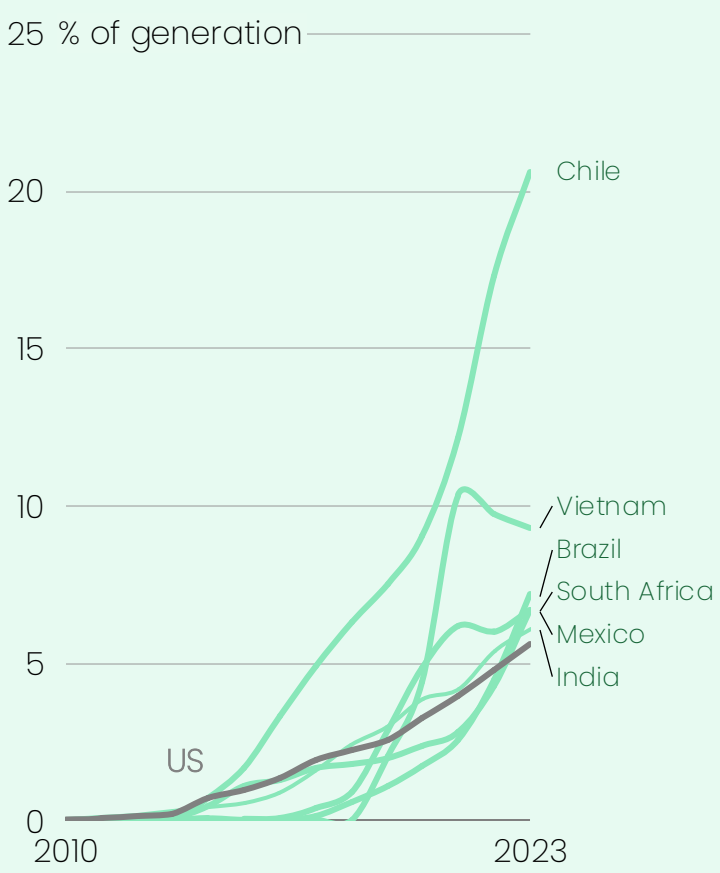
Emerging markets are leapfrogging

Two thirds are ahead of the US in solar deployment and a quarter in electrification

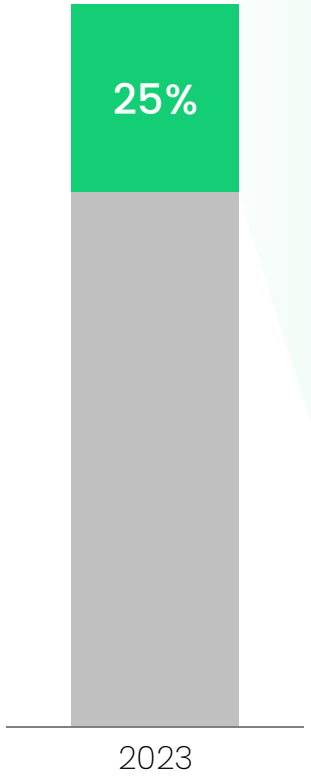
Share of EM ahead of US in solar uptake



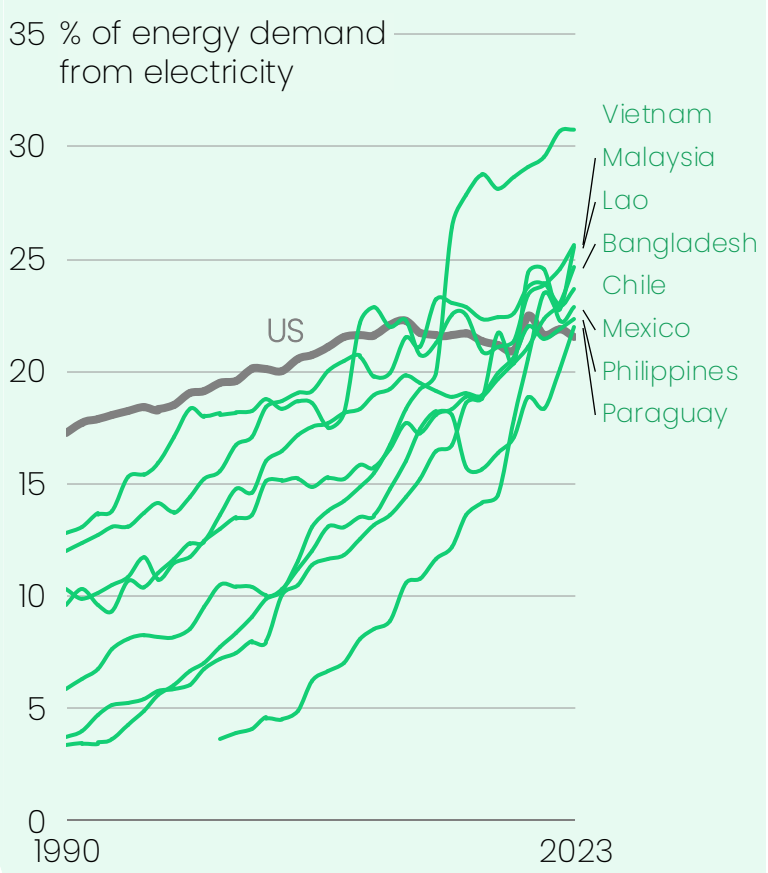
Example countries



Share of EM ahead of US electrification



Example countries



Sources: IEA; Ember analysis – Emerging markets (EM) defined as Latin America, Africa, South Asia and Southeast Asia and do not include the petroregions. Share of emerging markets is a share of electricity demand (l) and energy demand (r).

EMBER

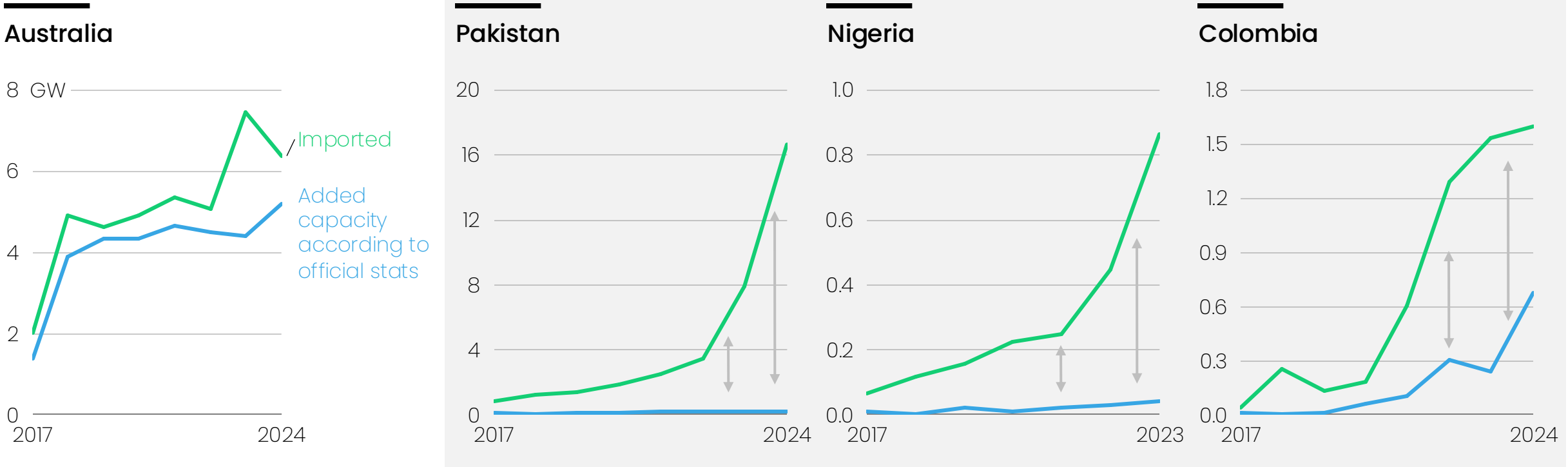
Change is happening faster than it can be recorded

Central grid statistics cannot keep up with what is happening on the ground

Solar capacity imported/installed

Imports generally convert to reported installed capacity within a year or so.

Across emerging markets, there is a growing gap between official statistics and import figures, which implies imported solar panels are not centrally connected and counted but installed decentrally.



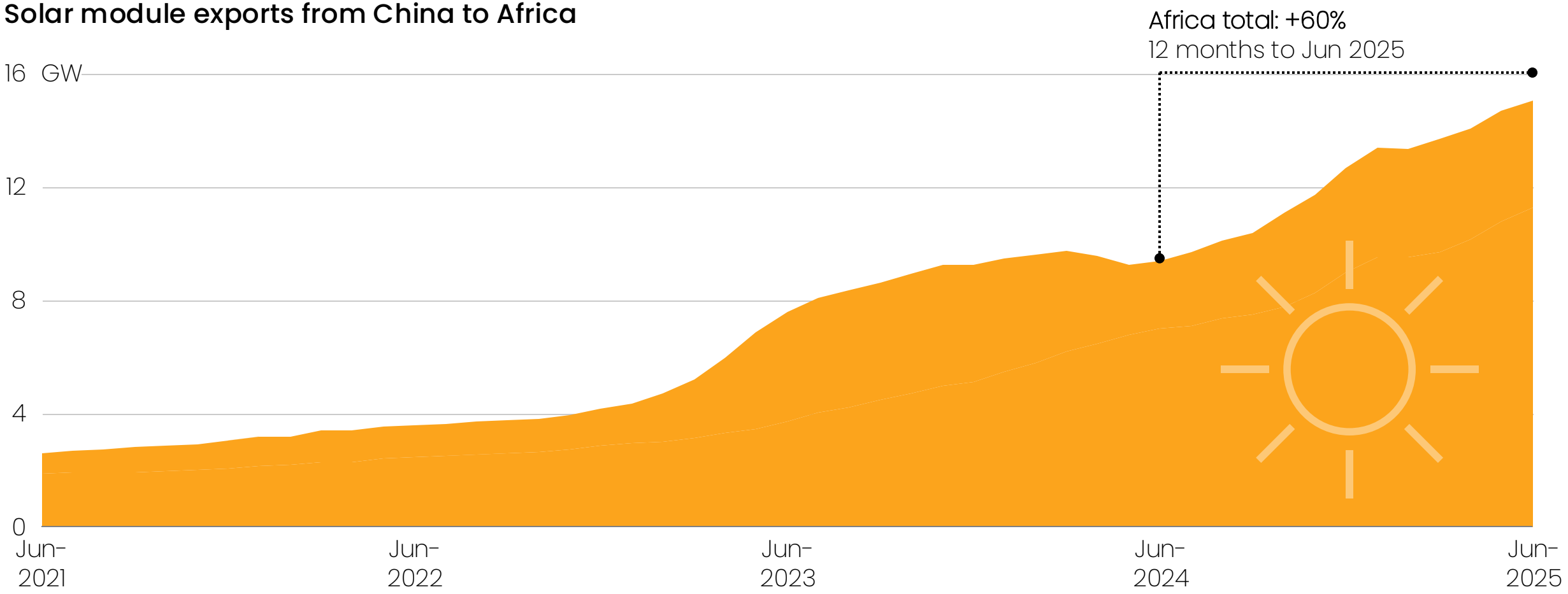
Sources: Ember data; Ember analysis • Notes: Imported statistics are in DC, while reported capacity is in AC. They should match within the expected inverter clipping ratio.

EMBER

Africa is turning to the sun

Solar imports are up by 60% in the last 12 months

Solar module exports from China to Africa



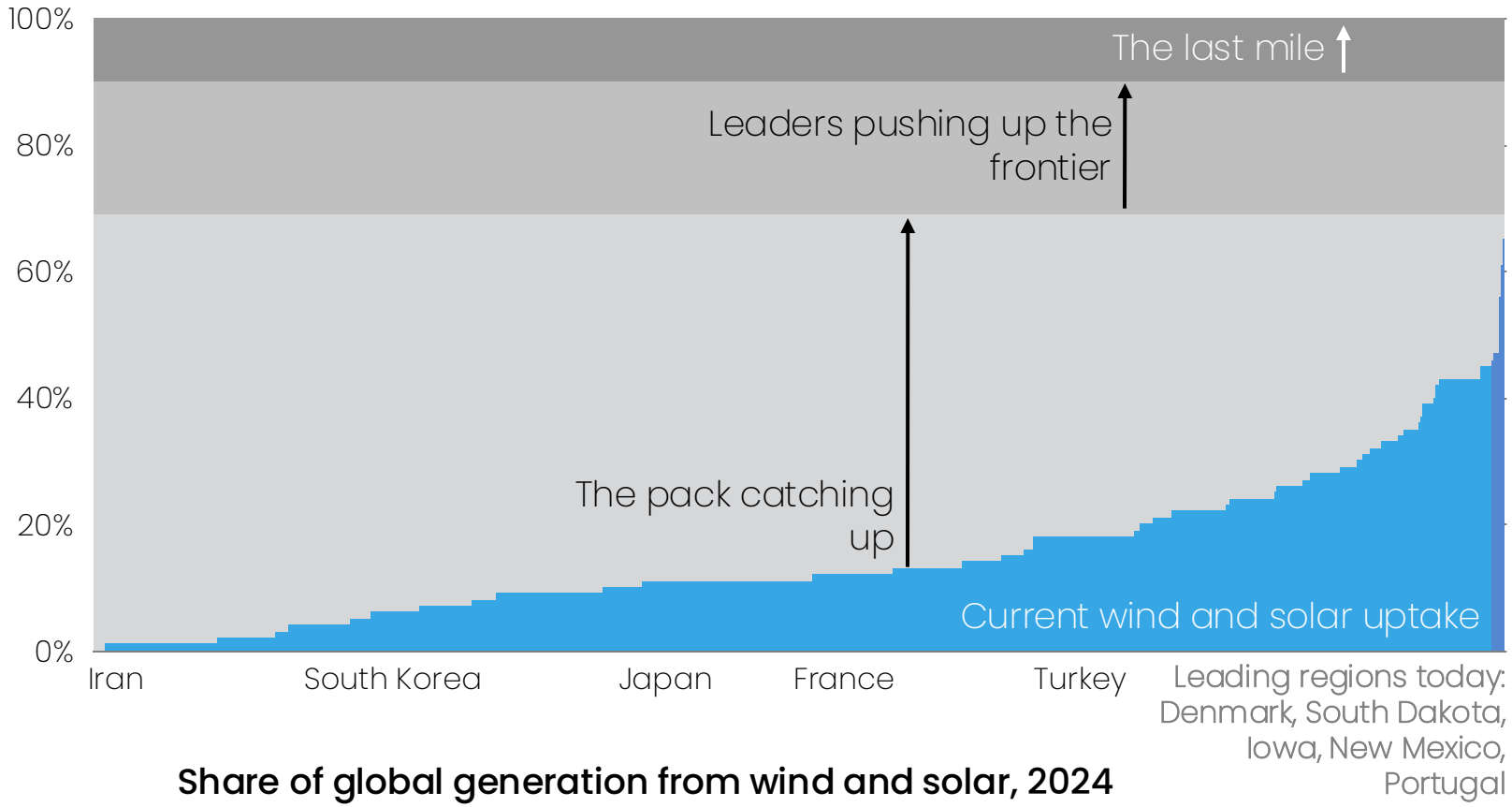
Sources: Ember China Solar Export Explorer

EMBER

The renewables ceiling is high and rising

Some 70-80% penetration from solar and wind is within our reach today

Wind and solar share of generation



Share of global generation from wind and solar, 2024

6 solutions to manage variability

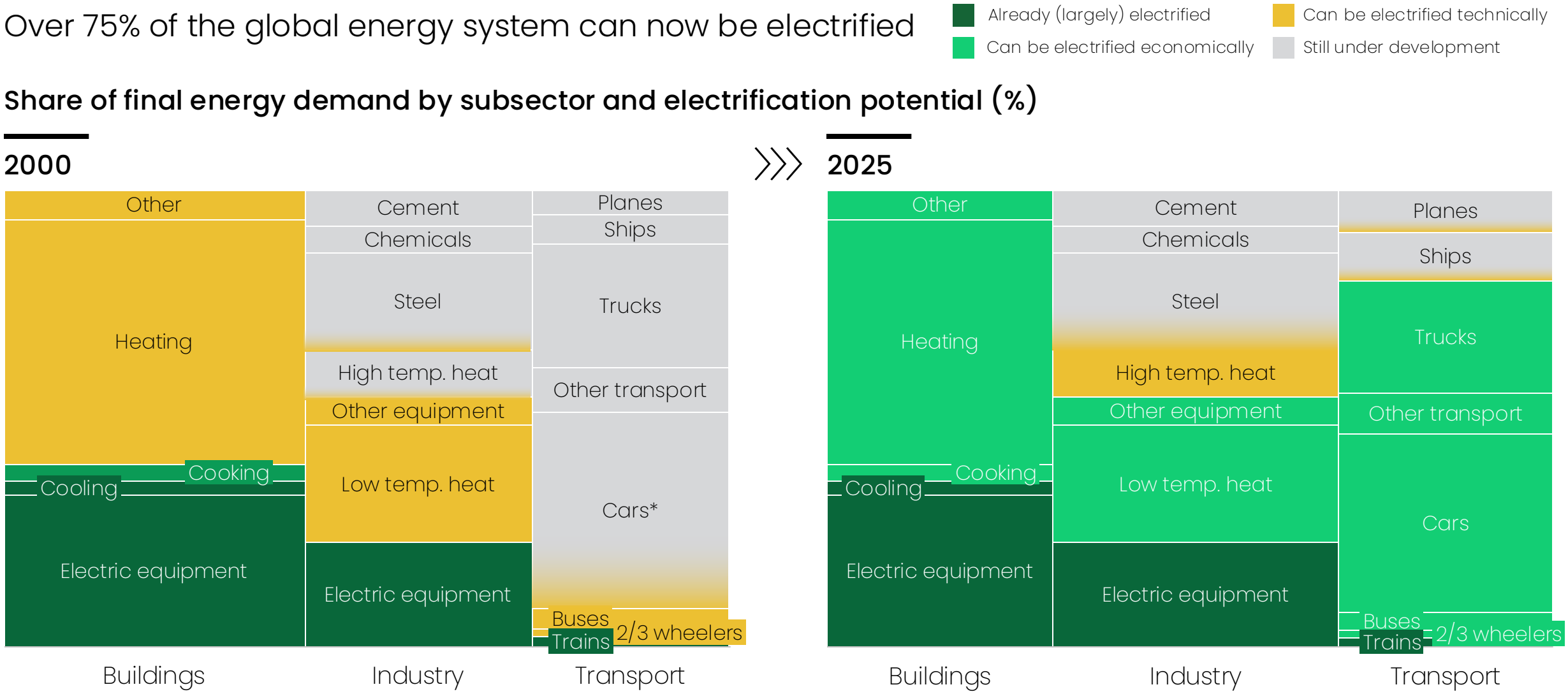
- Demand side flexibility
- Flexible generation
- Smarter grids
- Bigger grids
- Energy storage
- Overbuild solar & wind

Sources: Ember analysis; ETC – Power Systems transformation

EMBER

The electrification ceiling is high and rising

Over 75% of the global energy system can now be electrified

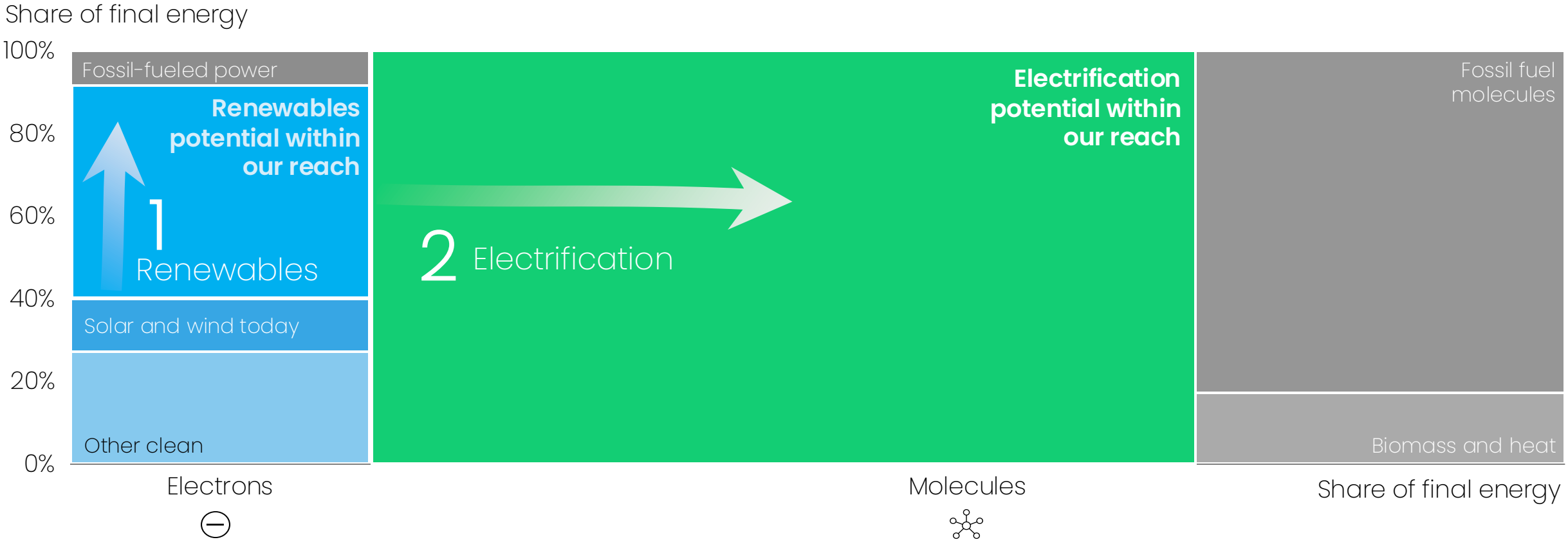


Sources: IIASA; IEA; BNEF; Ember analysis • Note: excluding feedstock *Technologies available for subset of total end-use with a clear path to expansion

The majority of the energy system is within reach

Renewables and electrification can triple

Global final energy demand in 2023



Sources: IEA, Ember – Note: Renewables potential includes solar and wind as well as other sources

EMBER

Chapter 3
Peak fossil demand

01

Peak fossil demand for electricity

The rapid growth of solar and wind enables them to take a rising share of the growth in electricity demand, with 64% of the growth since 2018. In half of the world we have already seen peak fossil fuels for electricity, and initial indications for the first half of 2025 are that China has also peaked.

02

Peak fossil demand for final energy

Peaks are cascading from one area to the next. Fossil demand has been flat for industrial energy since 2014, for buildings since 2018, and for road transport since 2019

Meanwhile two thirds of the world has already seen peak fossil demand for final energy.

03

Peak China means peak global fossil demand

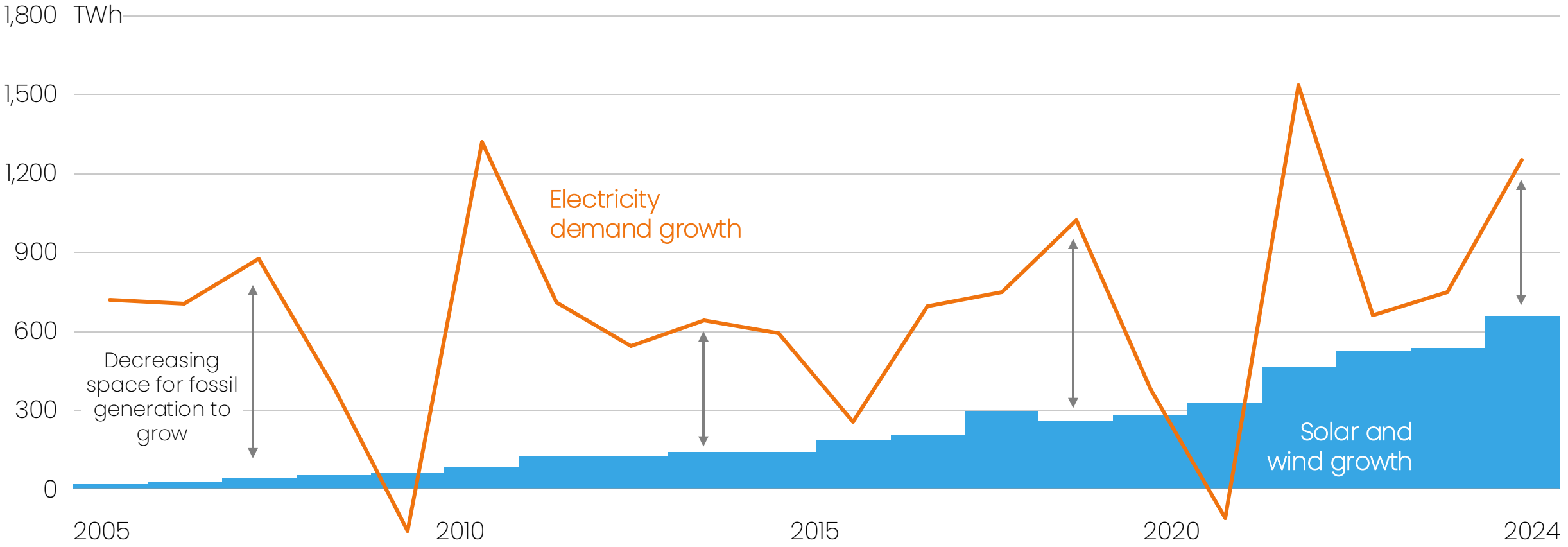
Fossil demand for final energy reached a peak in China in industry in 2012, in buildings in 2017, in transport in 2021, and in electricity in H1 2025. As a result total emissions are down by 1% year on year. Meanwhile, China is the pivot nation, as it accounted for 95% of the net growth in fossil fuel demand since 2018. As a result, a Chinese peak implies a global peak.

>> Return to Table of Contents

No space for fossils to grow in electricity

Solar and wind are about to take all the growth

Annual change in electricity generation



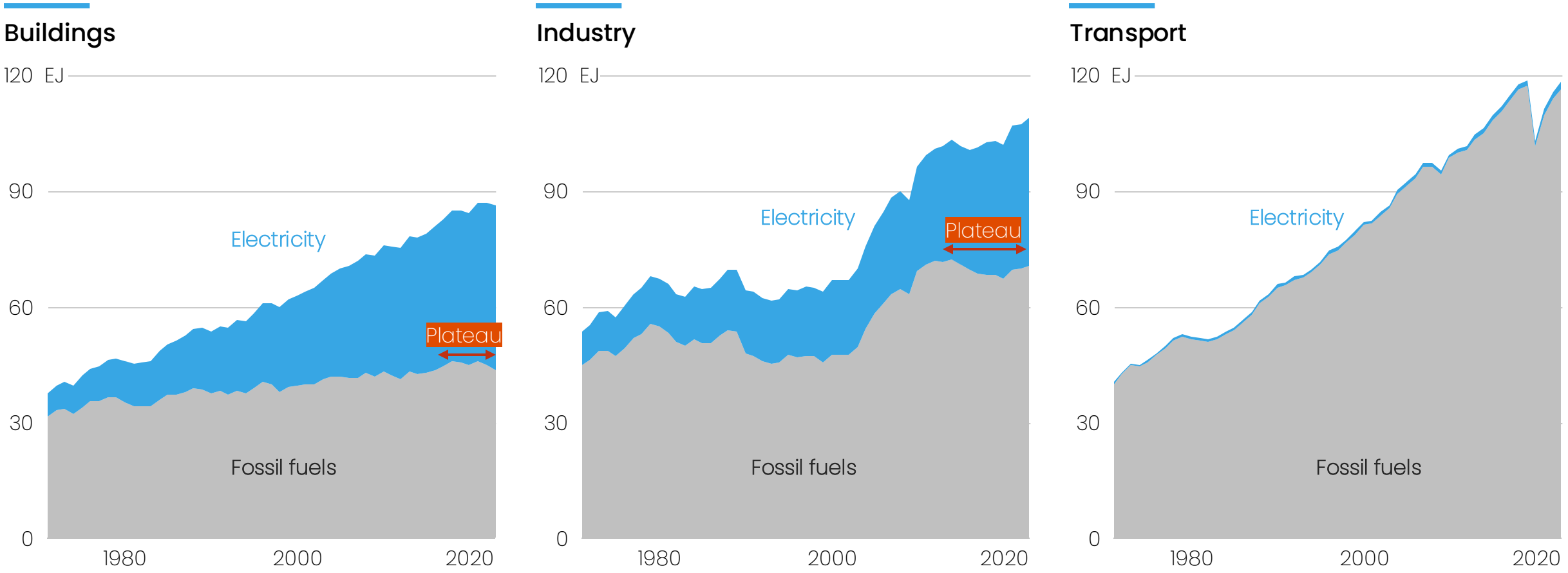
Source: Ember

EMBER

Electricity is taking all the growth in final demand

Peak fossils in industry was 2014 and in buildings was 2018

Final energy demand by sector



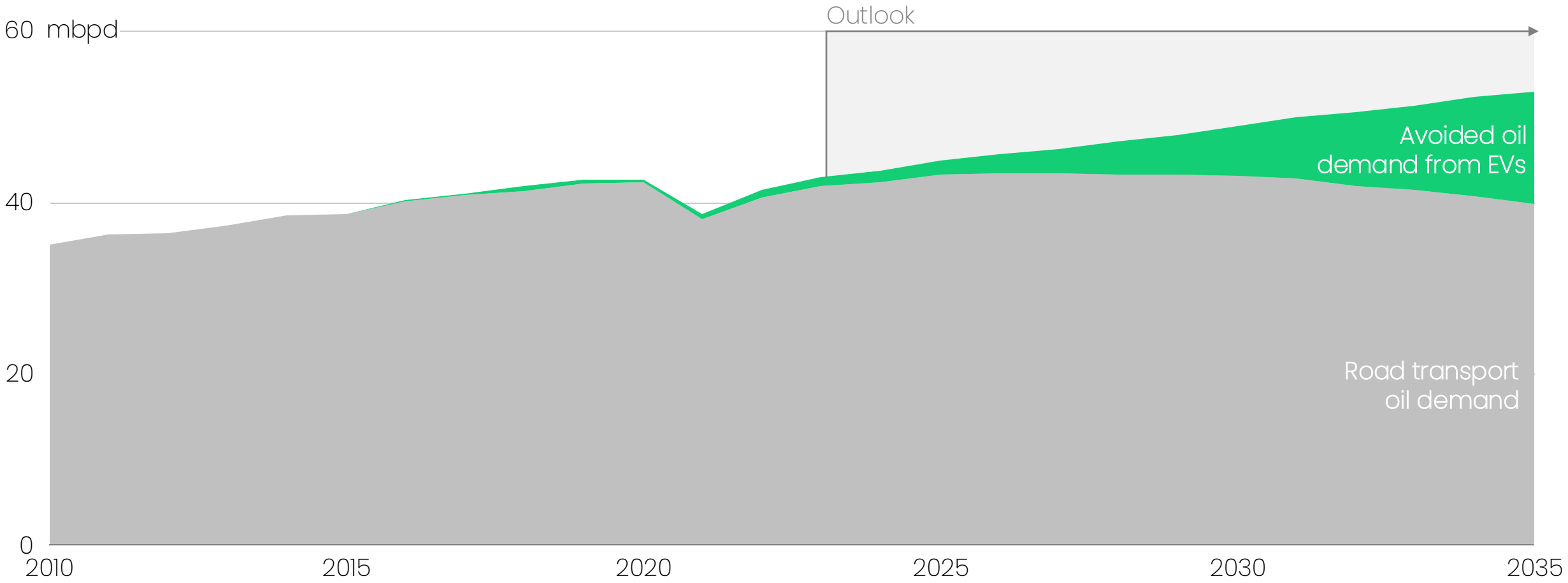
Sources: IEA WEB; Ember analysis. Note non-energy demand (42 EJ with growth of 1-2% pa) sits outside of industry in IEA WEB.

EMBER

EVs are driving a plateau in road transport

And road transport is 75% of transport energy demand

Oil demand in road transport in the IEA STEPS scenario and savings from EVs, 2010-2035

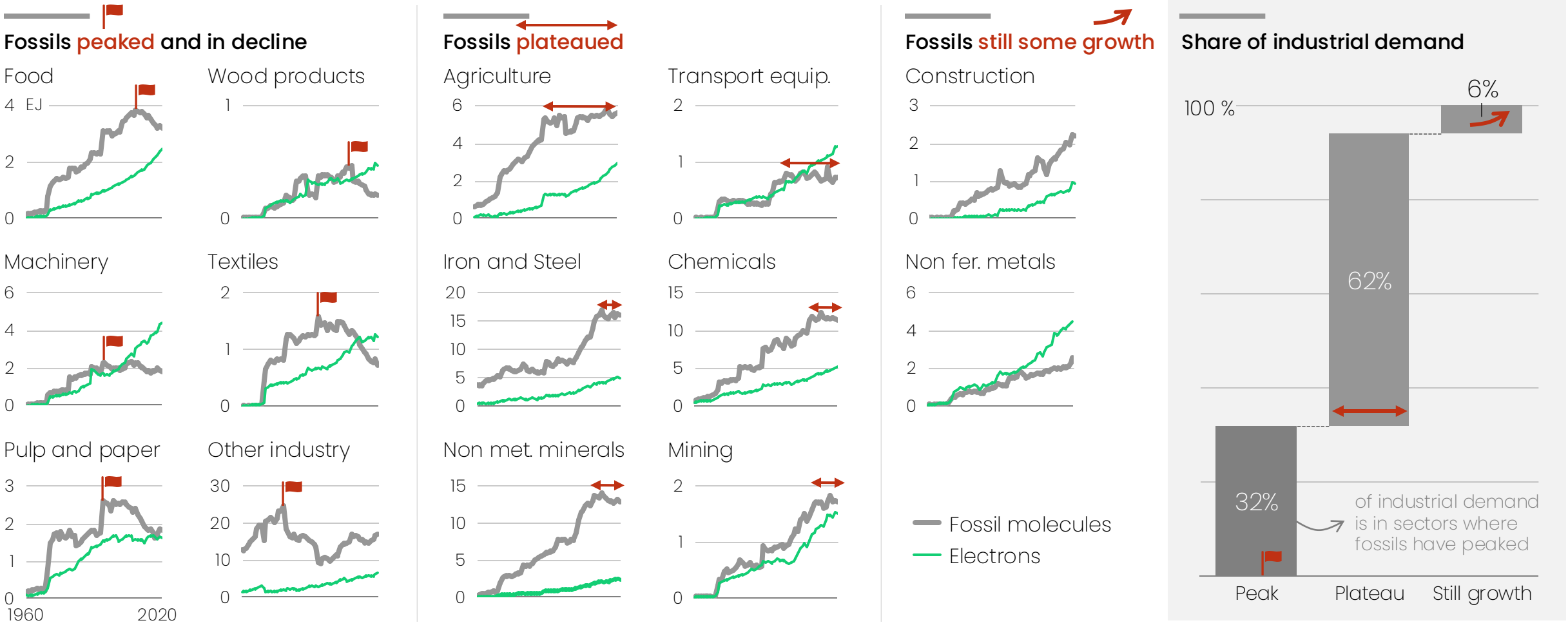


Sources: IEA WEO 2024 STEPS scenario – Note: STEPS is the IEA's most conservative scenario

EMBER

Industrial peaks everywhere

Only 6% of energy demand comes from sectors which still have structural fossil growth



Sources: IEA WEB; Ember analysis. Note: Feedstock demand of 42 EJ is not included in the industrial sector in IEA WEB

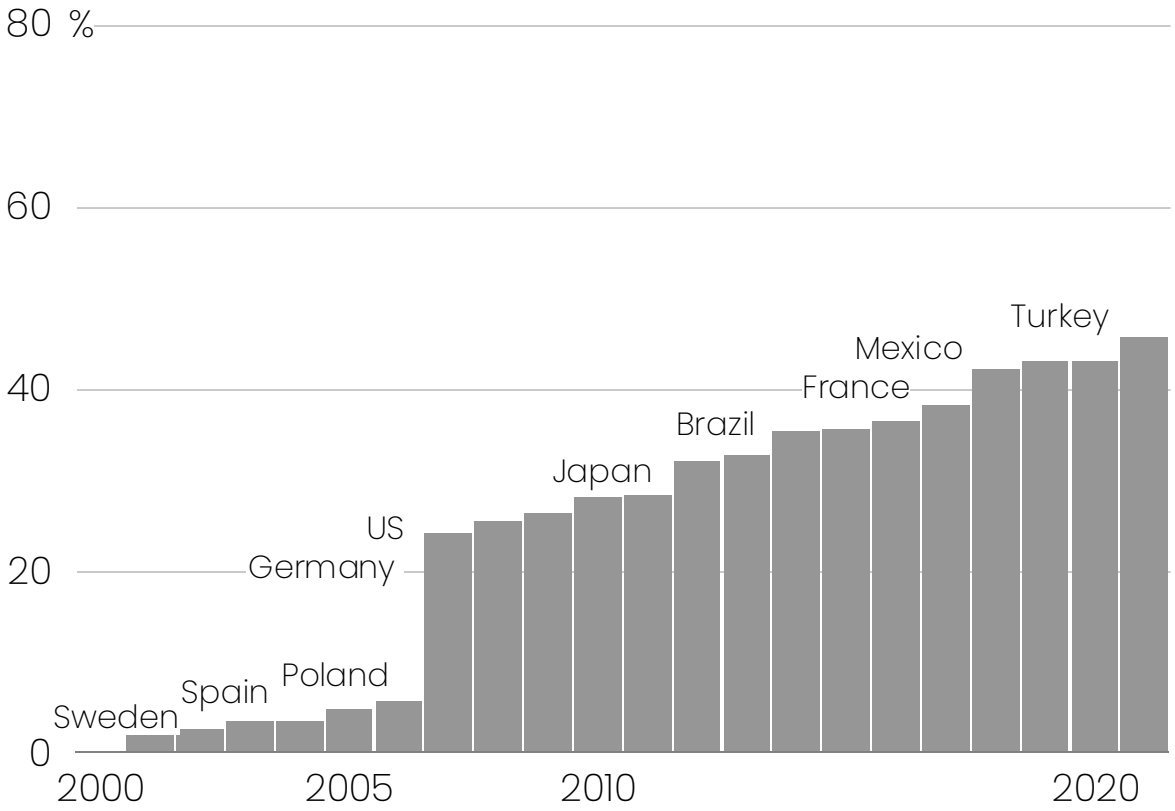
EMBER

Most of the world is past peak fossil fuels

Two-thirds of the world is past peak fossils in final energy and nearly half in power generation

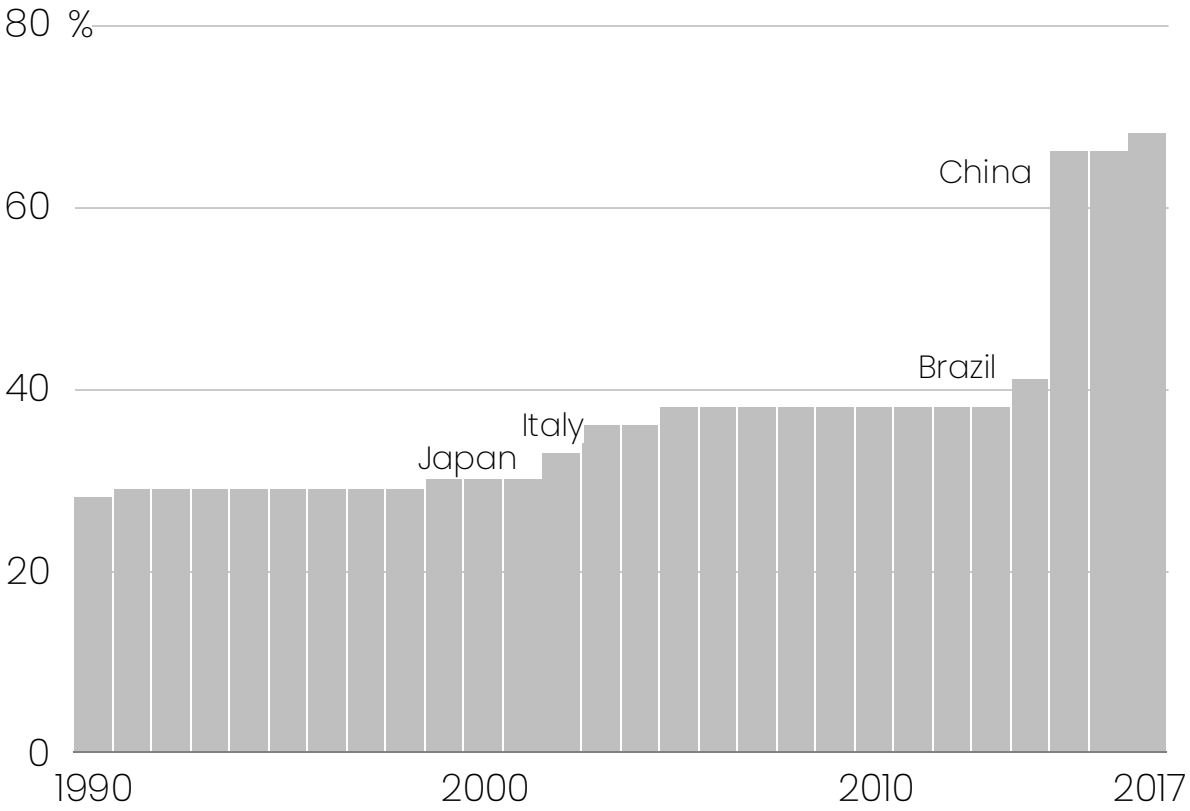
Share of the world past peak fossil demand for electricity

Driven by clean power and efficiency



Share of the world past peak final fossil energy demand

Driven by efficiency and electrification

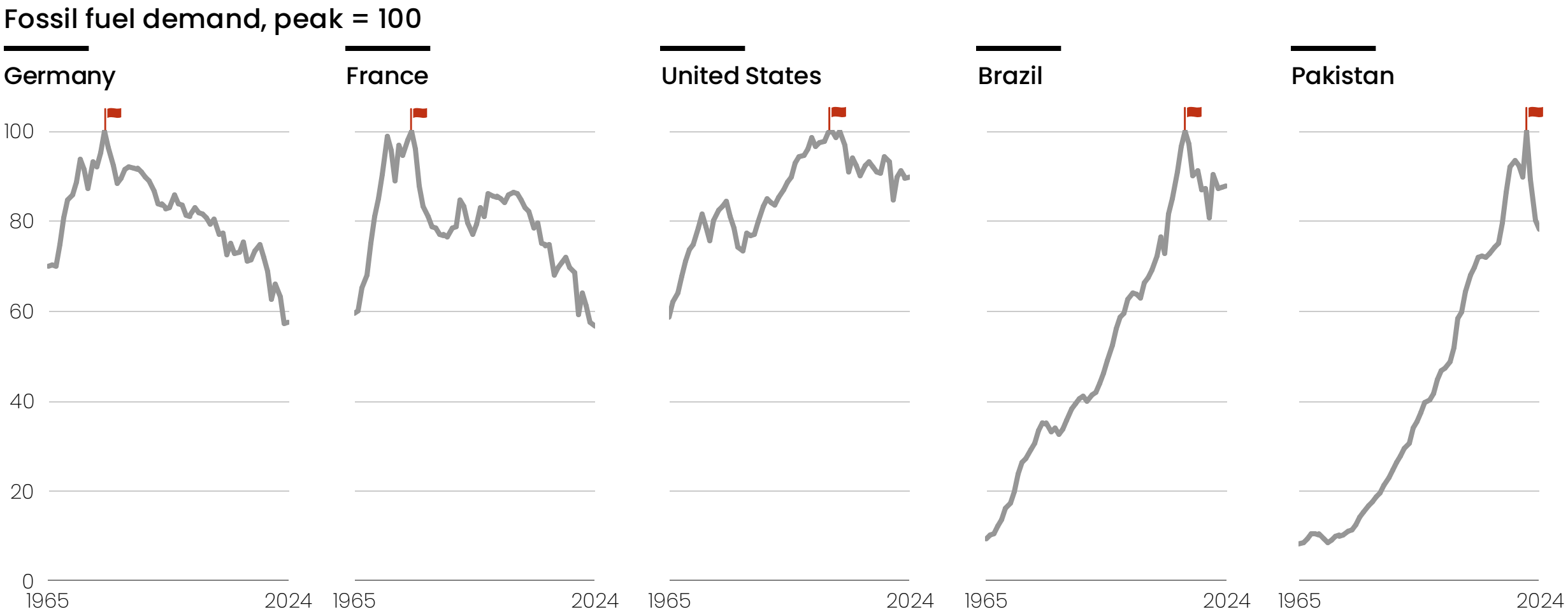


Sources: Ember. Share of world measured in 2023 energy. Final energy excludes non-energy.

EMBER

After the peak comes the fall

Countries don't have long plateaus although the world does



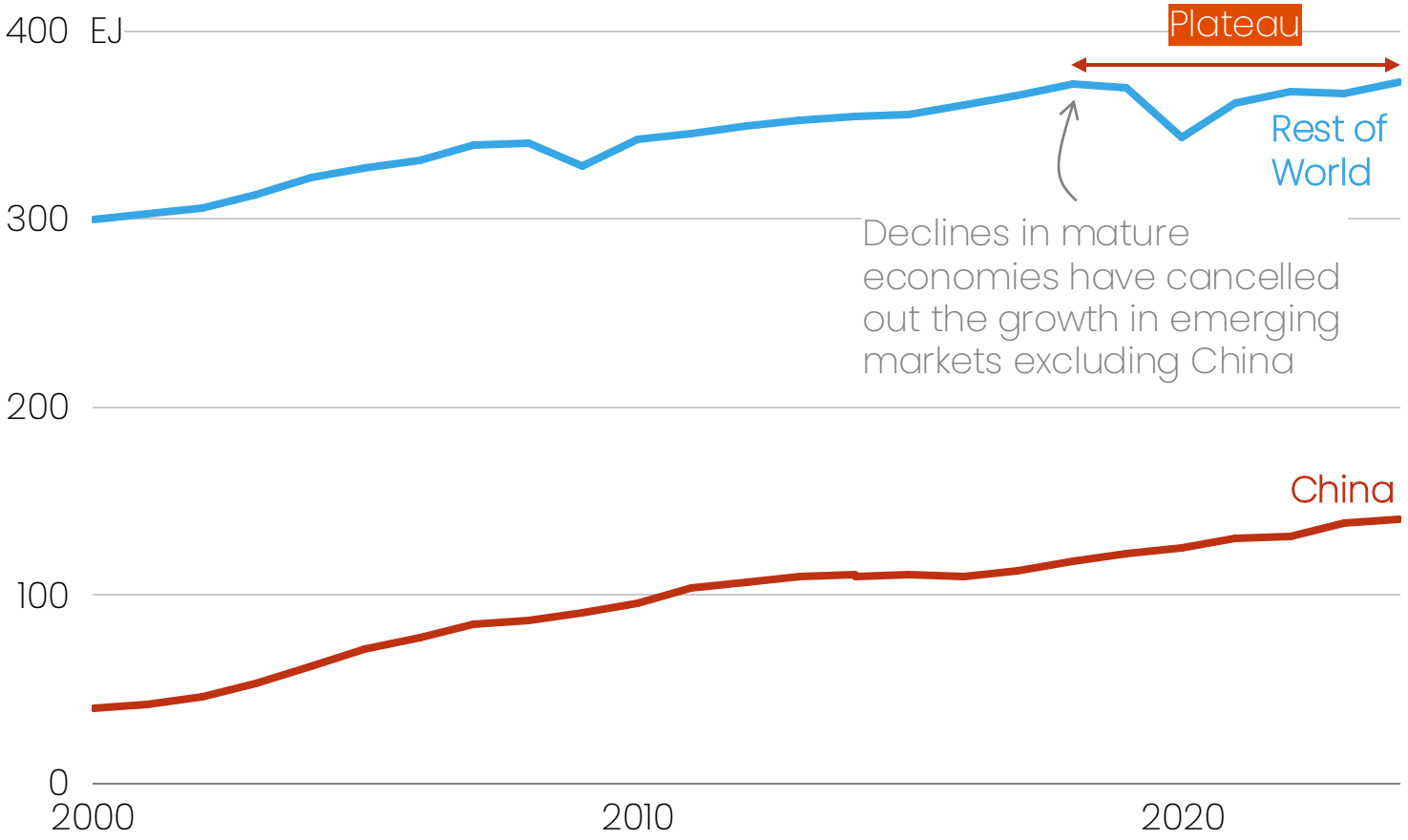
Sources: Energy Institute; Ember analysis

EMBER

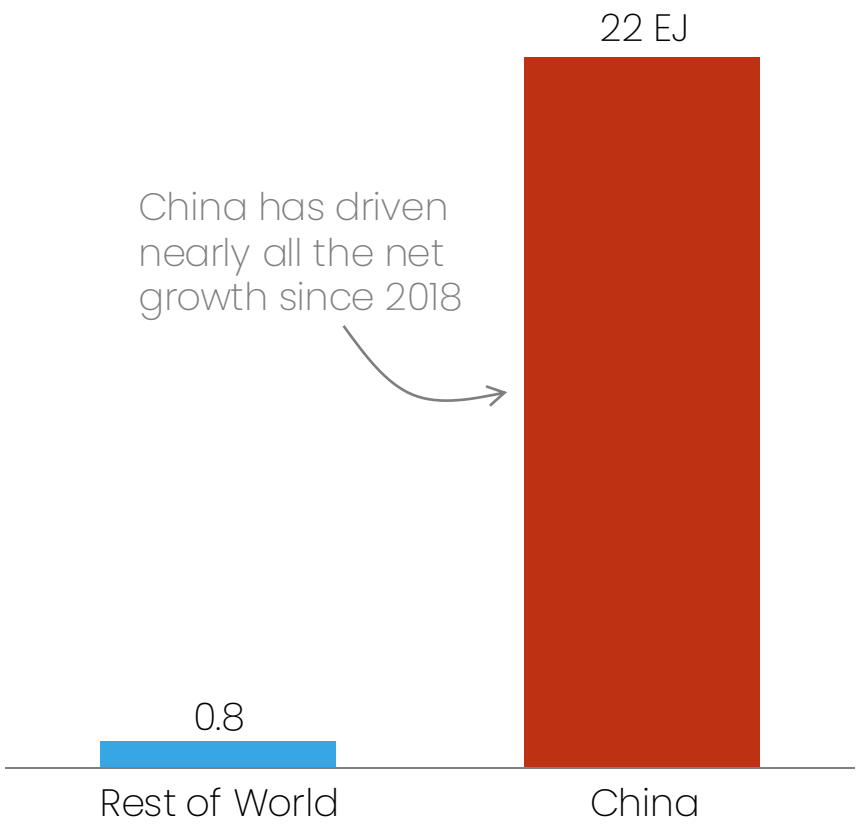
China is the pivot nation

Fossil fuel demand has already reached a plateau outside China

Primary fossil fuel demand



Change in fossil fuel demand 2018-2024



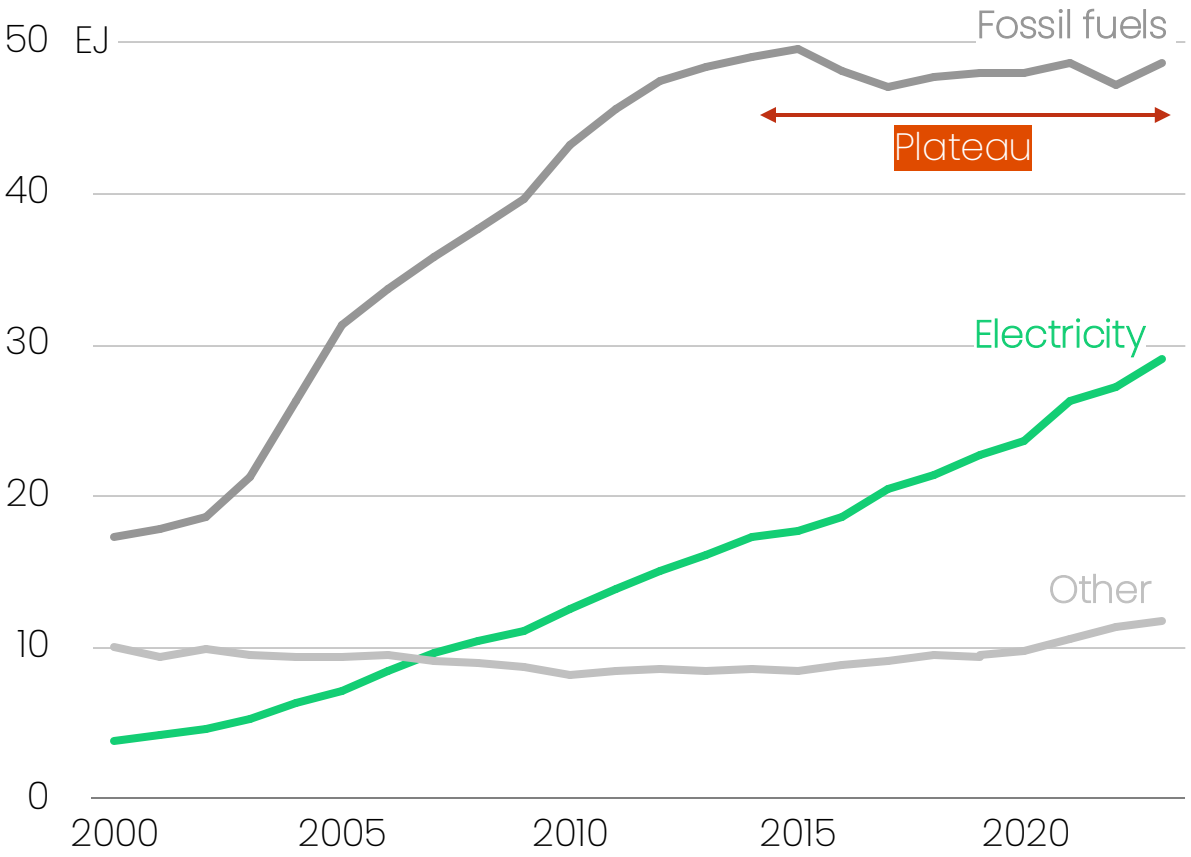
Sources: Energy Institute, Ember analysis

EMBER

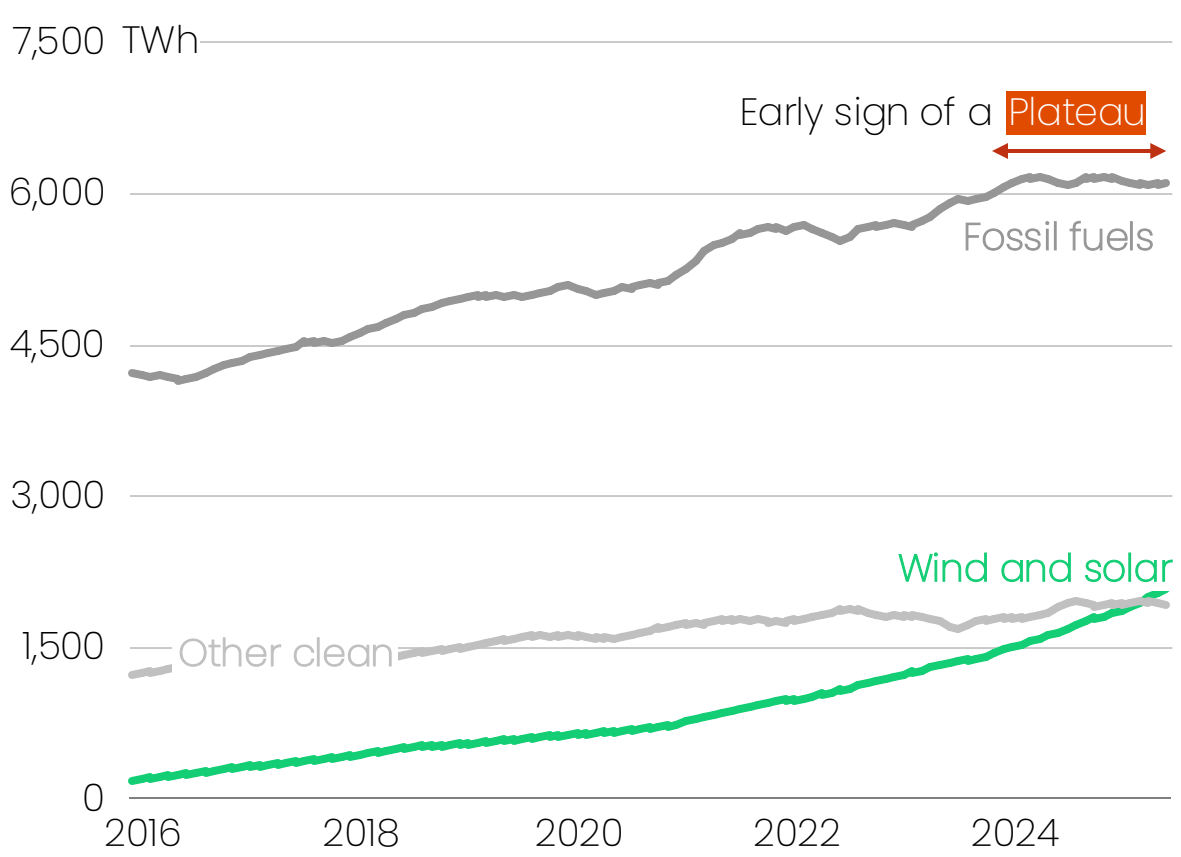
Fossil fuel demand is peaking in China

Final fossil demand stopped growing in 2014 and fossil electricity in H1-2025

Final energy consumption



Electricity generation, 12-month rolling sum



Sources: IEA WEB; Monthly electricity data, Ember. Note: final energy excludes non-energy.

EMBER

Chapter 4
Three fundamental drivers of change

Physics
Electrotech is more efficient than alternatives

Economics
Electrotech as a technology has learning curves and growth curves

Geopolitics
Electrotech is a key tool of energy security

>> Return to Table of Contents

EMBER

Chapter 4.1
The physics of change

01

Fossil fuels are very inefficient

The fossil fuel system wastes two thirds of its primary energy. $4.6 trillion a year goes up in smoke, and this sets up a very attractive environment for more efficient solutions.

02

Electrotech is three times more efficient

Electrotech is three times more efficient than fossil tech in sectors that make up two thirds of fossil fuel demand: electricity; road transport; and low temperature heat. Fossil fuels have to be burnt, requiring 17,000 million tonnes (mt) a year to be shipped around the world. Electrotech needs annual deployment of under 300 mt to build out the infrastructure required to harness the sun and wind.

03

Electrotech beats the rest of cleantech

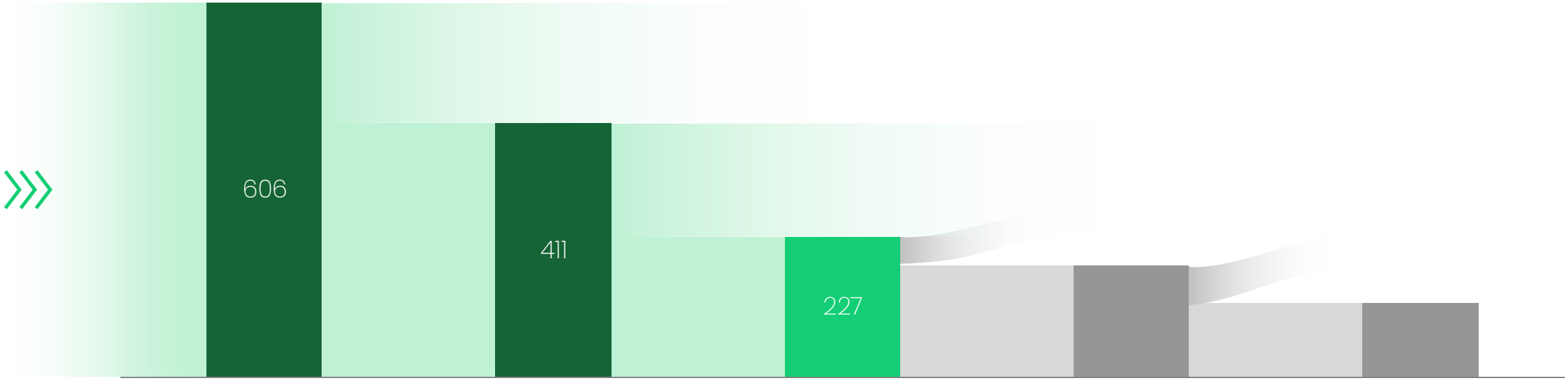
Electrotech is far more efficient than other cleantech solutions like CCS, biomass or hydrogen.

>> Return to Table of Contents

EMBER

Energy is all about efficiency

At its core, the energy system is about converting energy into useful forms as efficiently as possible



	Primary energy Energy going into the global energy system	**Final energy** Energy delivered to consumers	**Useful energy** Energy turned into functional forms	**Energy services** Useful energy turned into activities	**Prosperity** Activities turned into value
Examples	e.g., crude oil, coal	e.g., gasoline, electricity	e.g., hot water, vehicular motion	e.g., goods transported, ton steel produced	e.g., wealth, satisfaction, happiness

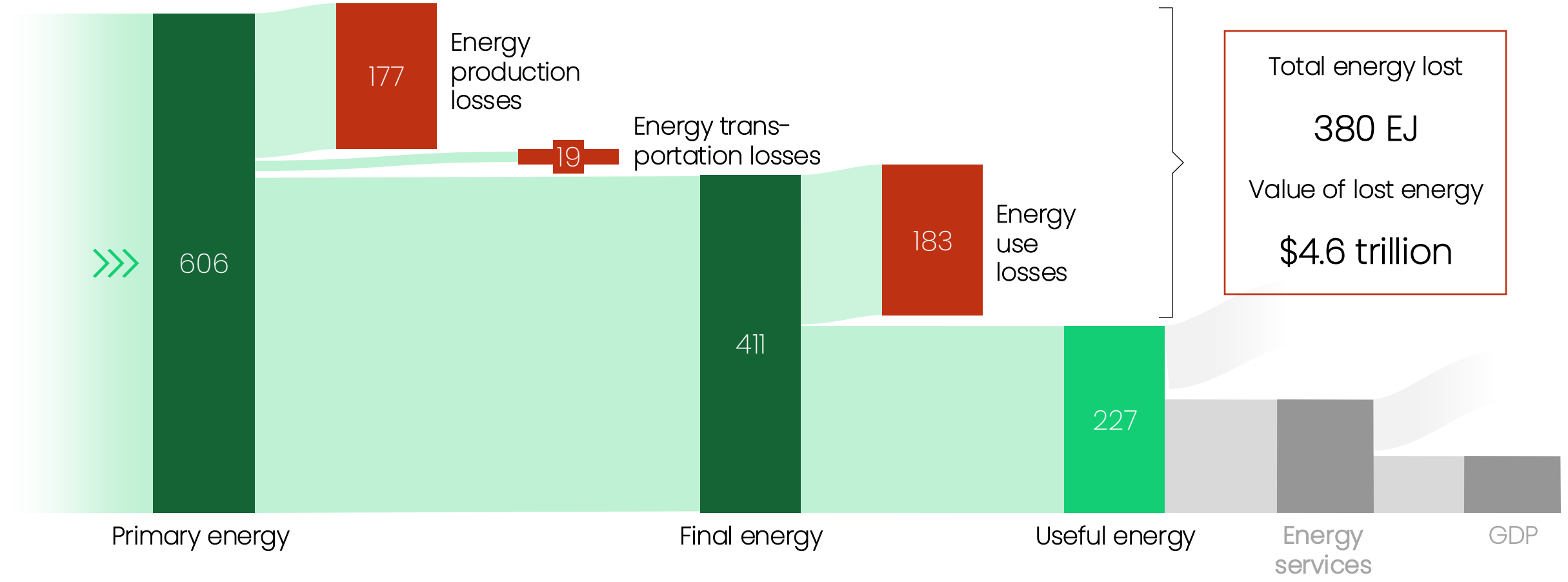
WHAT EVERYONE TALKS ABOUT ← → **WHY WE ACTUALLY CARE ABOUT ENERGY**

Sources: RMI

The current fossil energy system is incredibly inefficient

We lose some two thirds of the energy we put into the system

Global energy flows and waste, EJ per year, 2019



Sources: RMI

EMBER

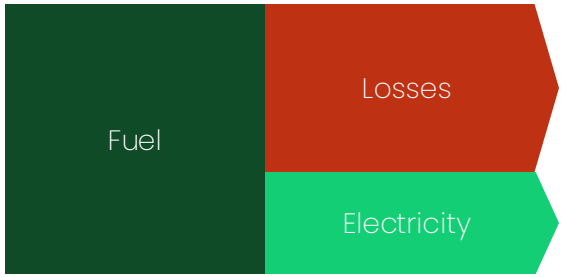
Electrotech is 3x more efficient

It offers a leap in energy efficiency across the economy

Supply

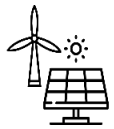
Electricity generation

Fossil thermal



30-40% efficiency

Wind & solar

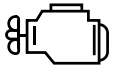


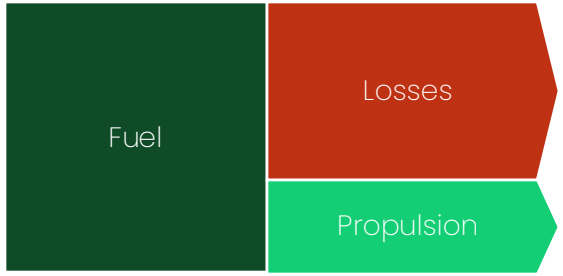
100% efficiency

Demand

Transport

Internal combustion engine





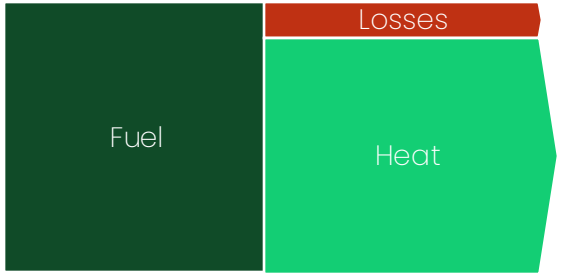
25-40% efficiency

Electric vehicles

80-90% efficiency

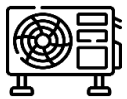
Heating

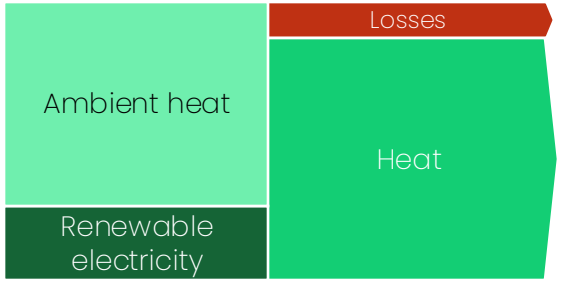
Gas boiler



85% efficiency

Heat pumps





300-400% efficiency

2-3x
as efficient

2-4x
as efficient

3-4x
as efficient

Sources: IEA, IIASA, Visual adapted from Prof. Tomas Kåberger and RMI • Note: heating refers only to low temperature heating

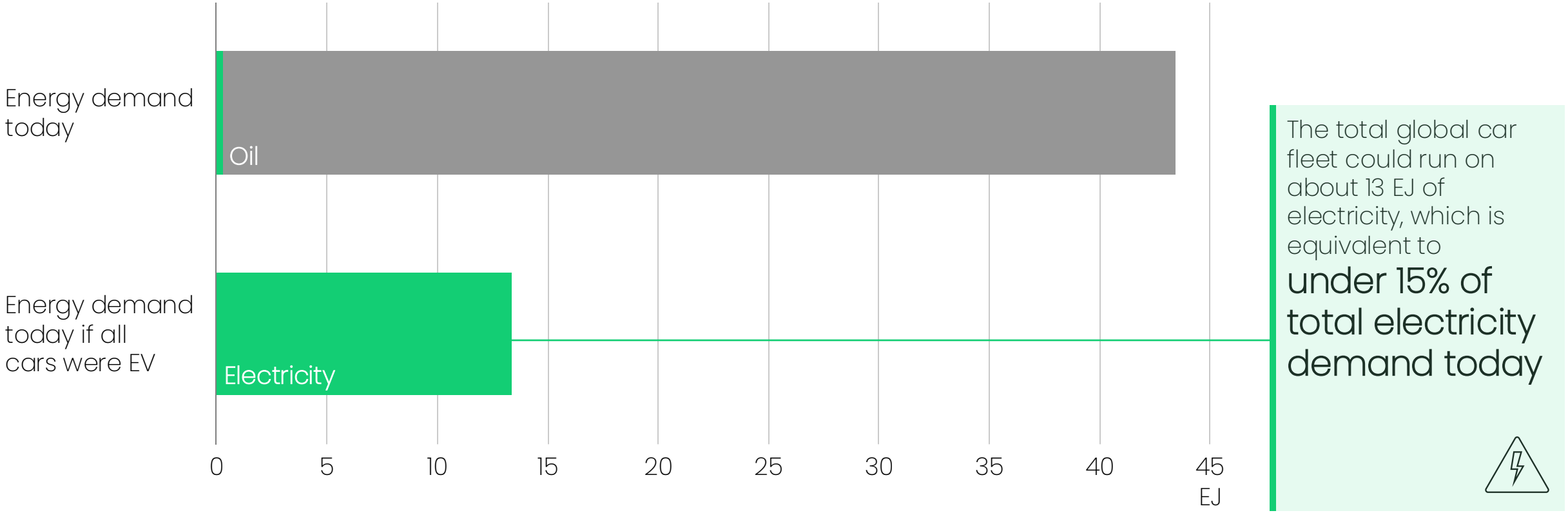
EMBER

Electrotech enables us to get much more for much less

Electrotech can provide the same useful services for three times less final energy

Example: passenger cars

Final energy demand



The total global car fleet could run on about 13 EJ of electricity, which is equivalent to

under 15% of total electricity demand today

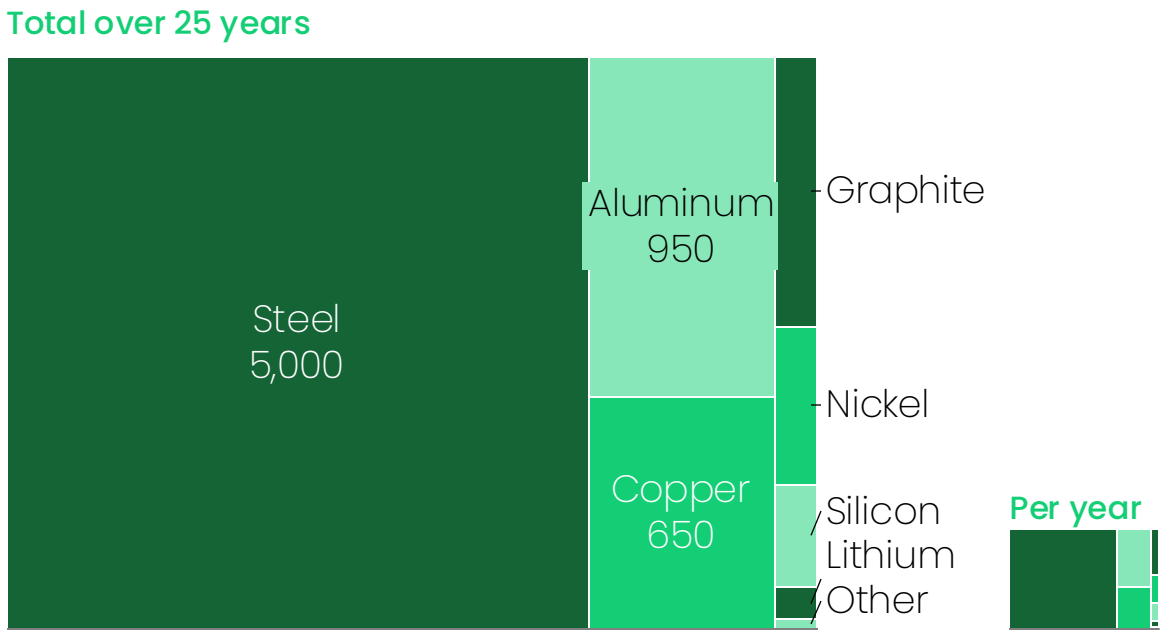
Sources: BNEF; Ember analysis

EMBER

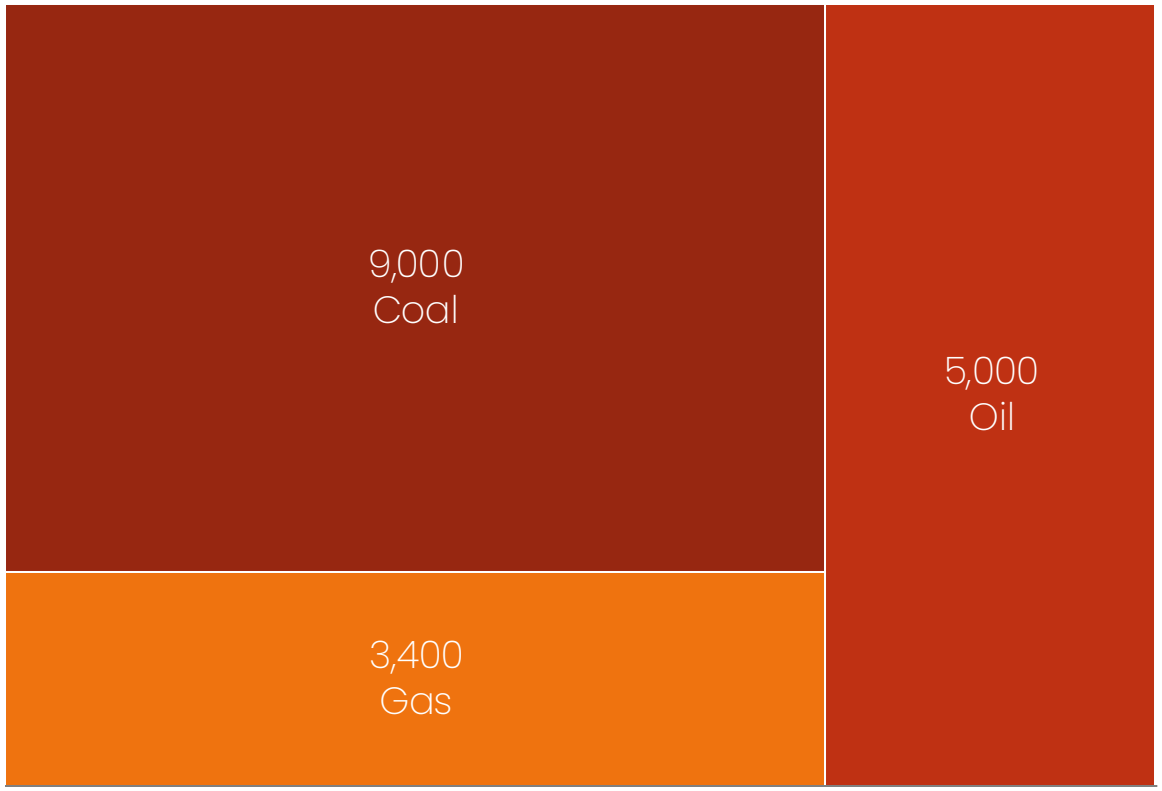
The unbearable heaviness of the fossil fuel system

The fossil fuel system requires over 50x more materials than electrotech

Total material demand for the energy transition for 25 years (*2024-2050*), Million metric tons



Fossil fuel extraction *per year today*, Million metric tons

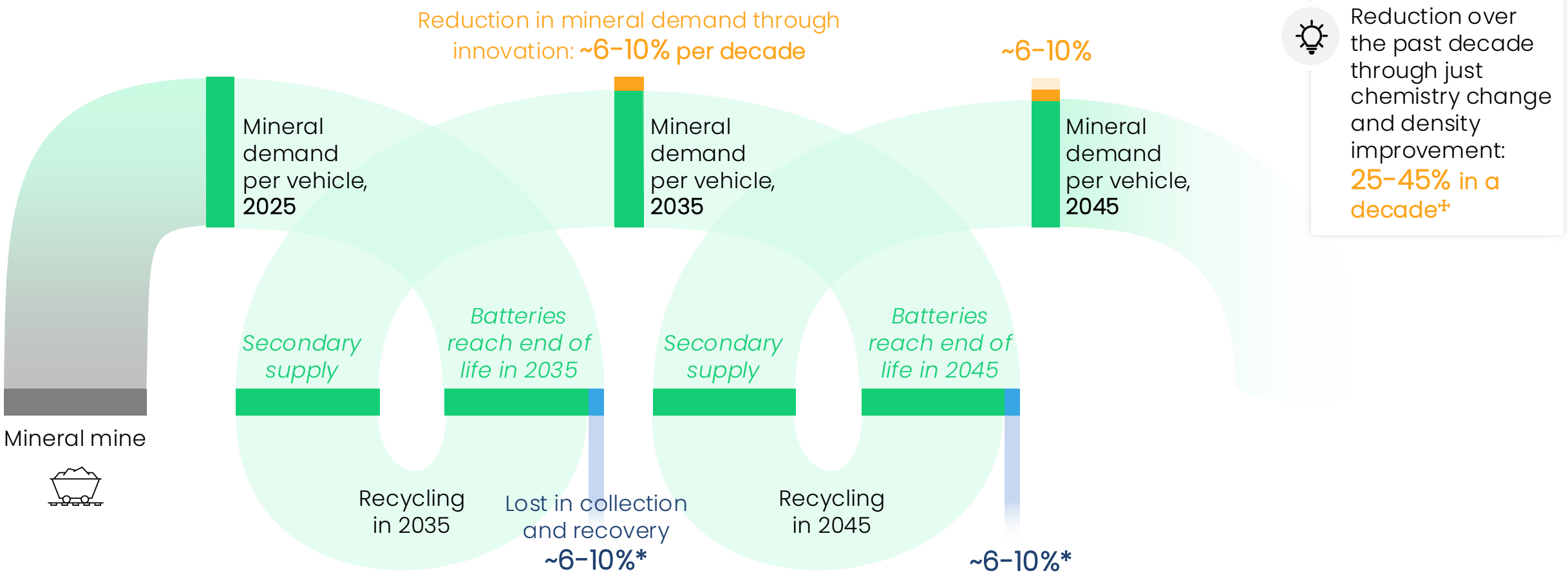


Sources: ETC; EI; Ember analysis

EMBER

Borrowing, not burning

If you recycle batteries and improve performance, you don't need to extract new minerals



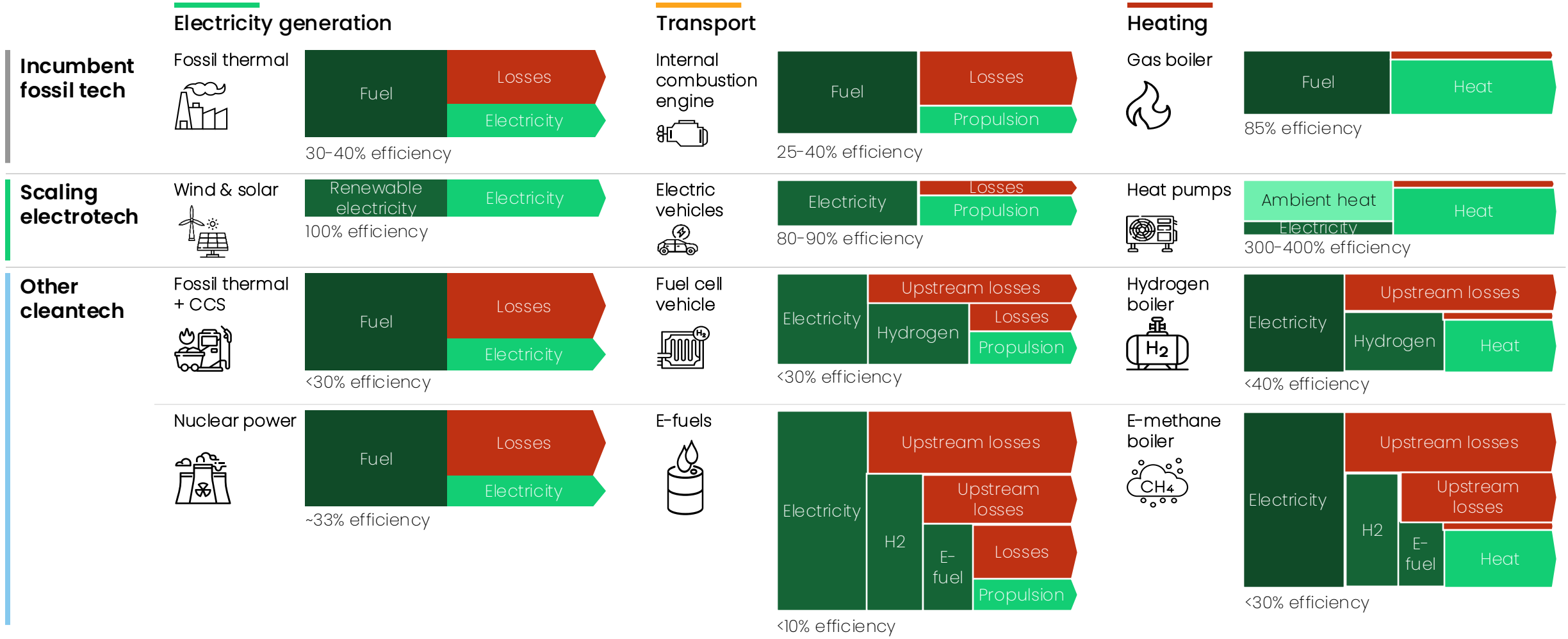
Reduction over the past decade through just chemistry change and density improvement: 25-45% in a decade‡

Sources: RMI • Notes: Useful battery lifetime of a decade is indicative; lifetimes are likely longer. * Accelerated case ‡ About 25% for lithium, about 50% or more for nickel and cobalt

EMBER

Efficiency differentiates electrotech from other cleantech

Molecule-based cleantech does not enjoy the tailwinds of being more efficient



Sources: IEA, IIASA, Visual adapted from Prof. Tomas Kåberger and RMI • Note: heating refers to low temperature heating

Chapter 4.2
The economics of change

01

Technologies have learning curves

Electrotech is small and modular with lots of opportunity to innovate. The more electrotech you deploy, the cheaper it gets because of learning curves of around 20% for every doubling of deployment. In contrast, fossil fuels need to fight a constant battle against depletion.

02

Technologies grow exponentially

Electrotech grows rapidly on standard S-curves that we have seen in many other technologies over decades. For 30 years, solar capacity has been doubling every three years on average, and since 2020 battery storage has been nearly doubling every year.

03

Electrotech makes you rich

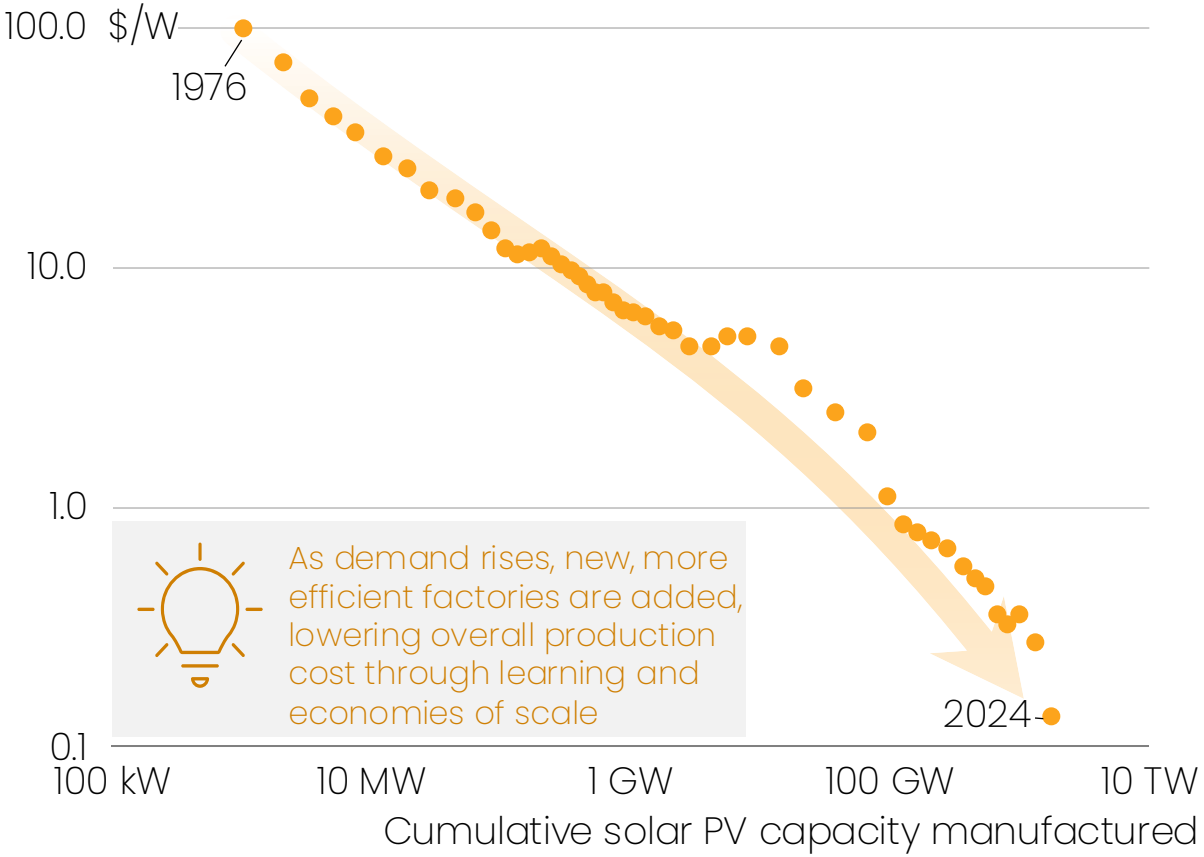
Electrotech drives GDP growth, powers the industries of the future and supplies all the expected growth in energy jobs.

>> Return to Table of Contents

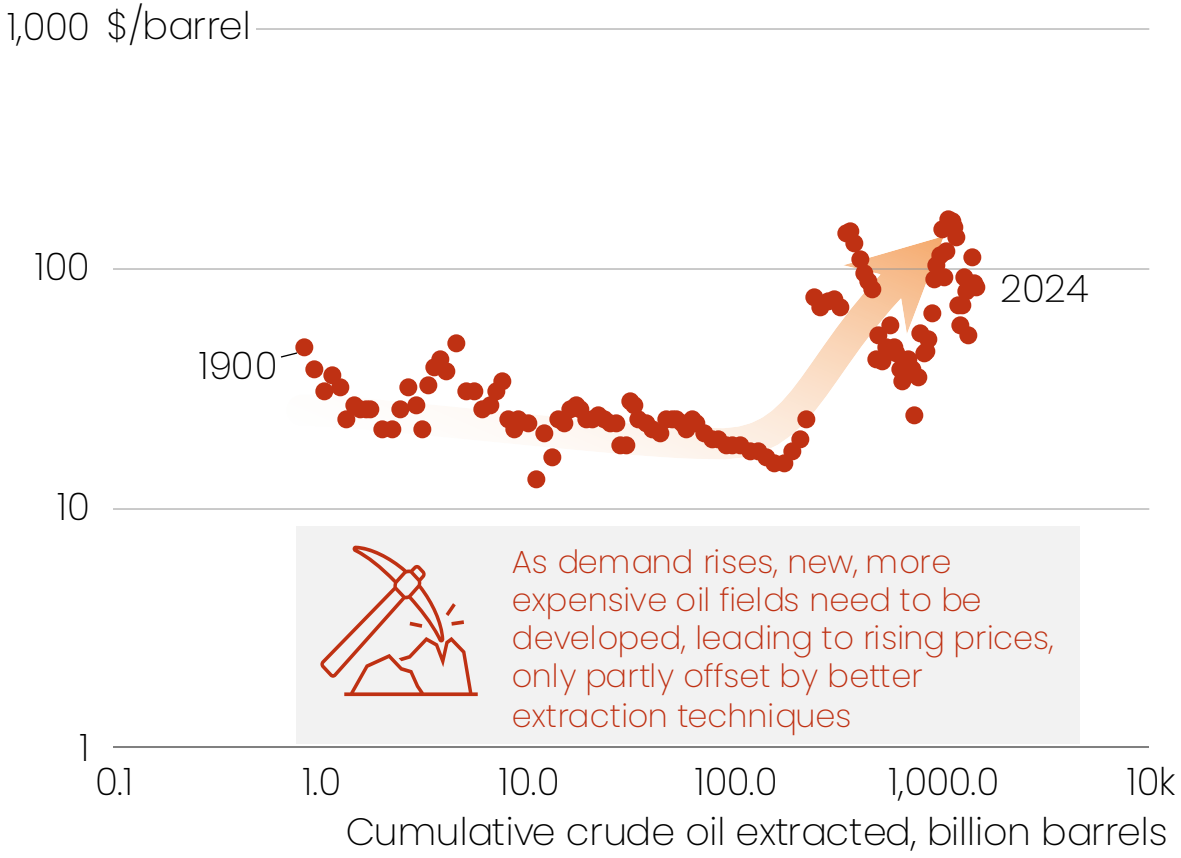
Learning beats digging

Electrotech gets cheaper with scale, whereas fossil fuels get more expensive

Solar panel price cost versus amount manufactured



Oil price versus amount extracted



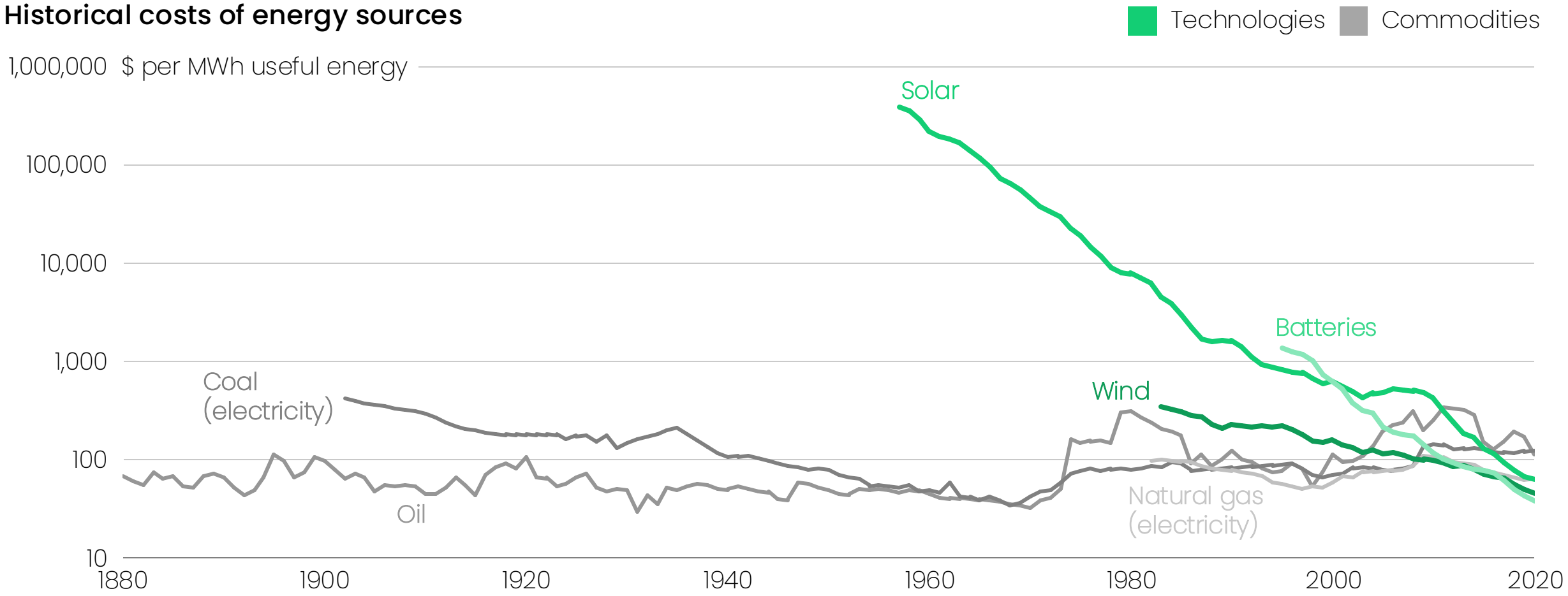
Sources: Rystad; BNEF; Ember analysis

EMBER

Technologies beat commodities on cost

Electrotech is the triumph of brain over brawn

Historical costs of energy sources



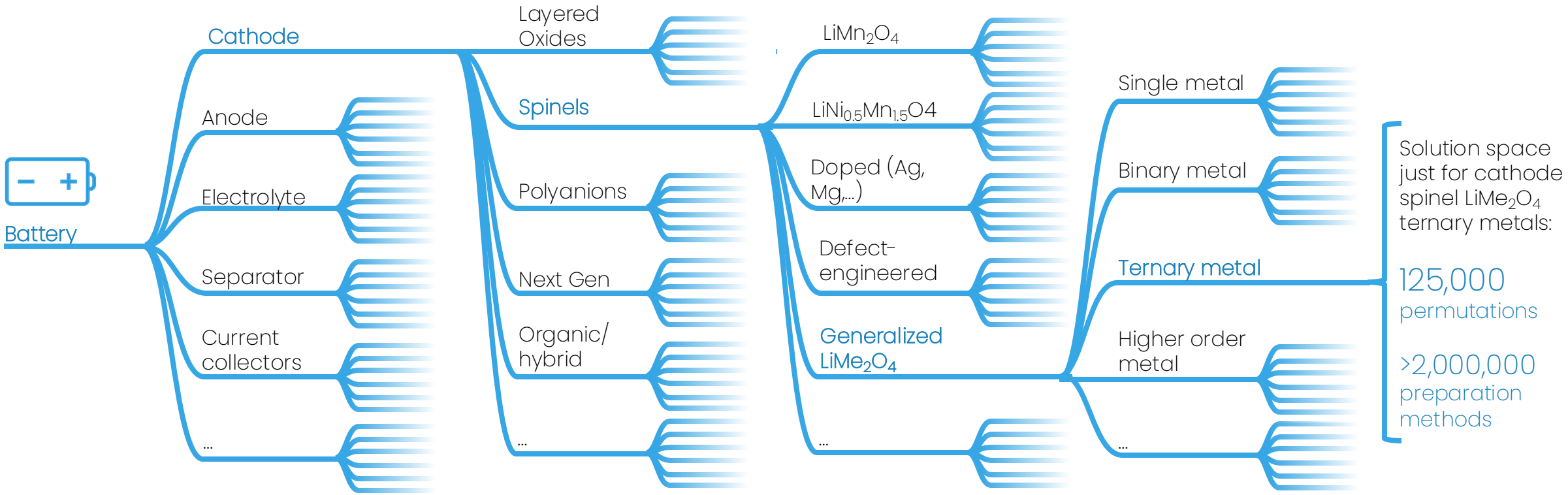
Sources: Way et al. 2022. Fossil fuel extraction has learning curves but empirically this has been matched by depletion.

EMBER

There is a huge solution space to explore

The electrochemical solution space underlying electrotech is enormous

Example: battery cell solution space



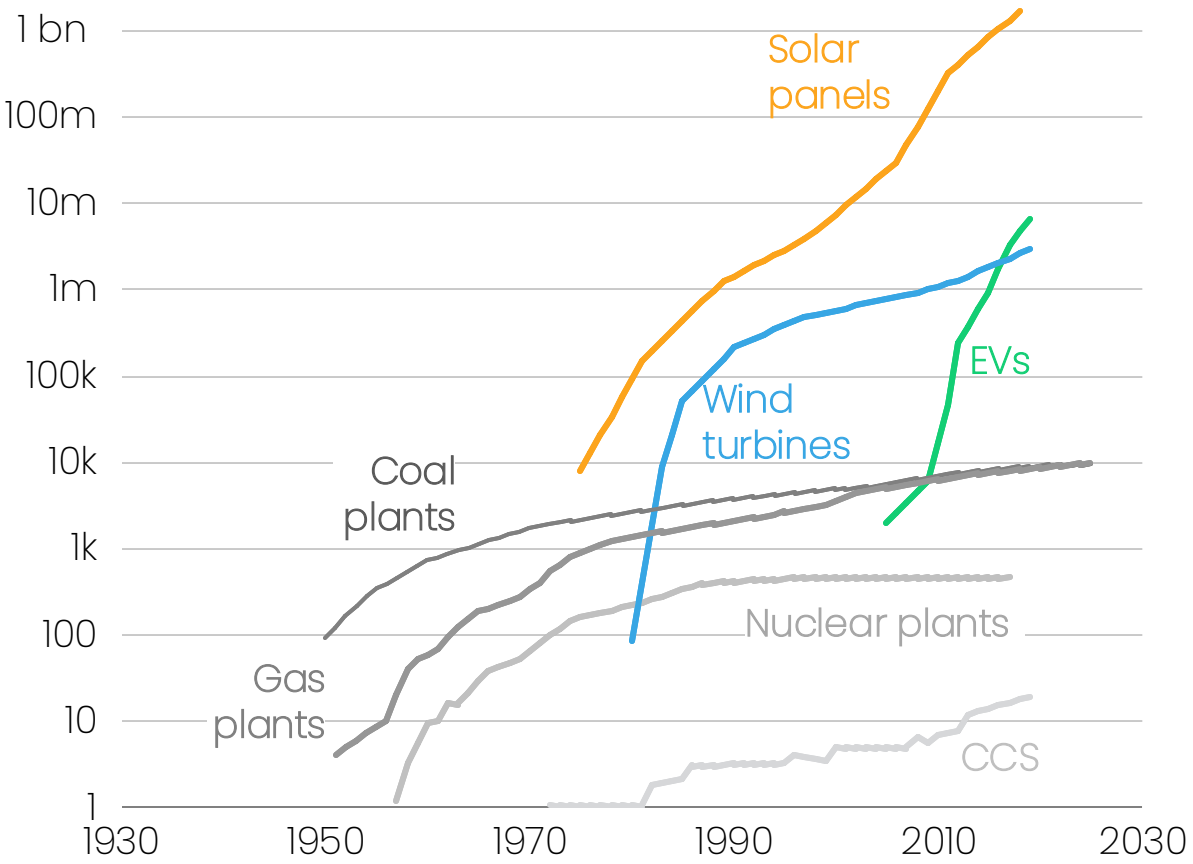
Sources: Volta Foundation; Yesuraj et al. (2024), Marincas et al. (2020), Liang et al. (2020), Choi et al. (2024), Nisar et al. (2021), Huang et al. (2021) – Note: Me = transition metal

EMBER

Learning by doing

Electrotech is small, modular and cheap, allowing for a lot of experimentation and learning

Cumulative units produced



Typical deployment effort

Solar panels
1-6 months
$ 100/unit

EVs
1-6 months
$ 30,000/unit

Wind turbines
6-24 months
$ 3,000,000/unit

Gas plants
3-4 years
$ 800,000,000/unit

Coal plants
4-6 years
$ 3,000,000,000/unit

Nuclear plants
6-10 years
$ 7,000,000,000/unit

CCS projects
5-10 years
$ 1,000,000,000/unit

Sources: Global Energy Monitor, Greg Nemet, Ember

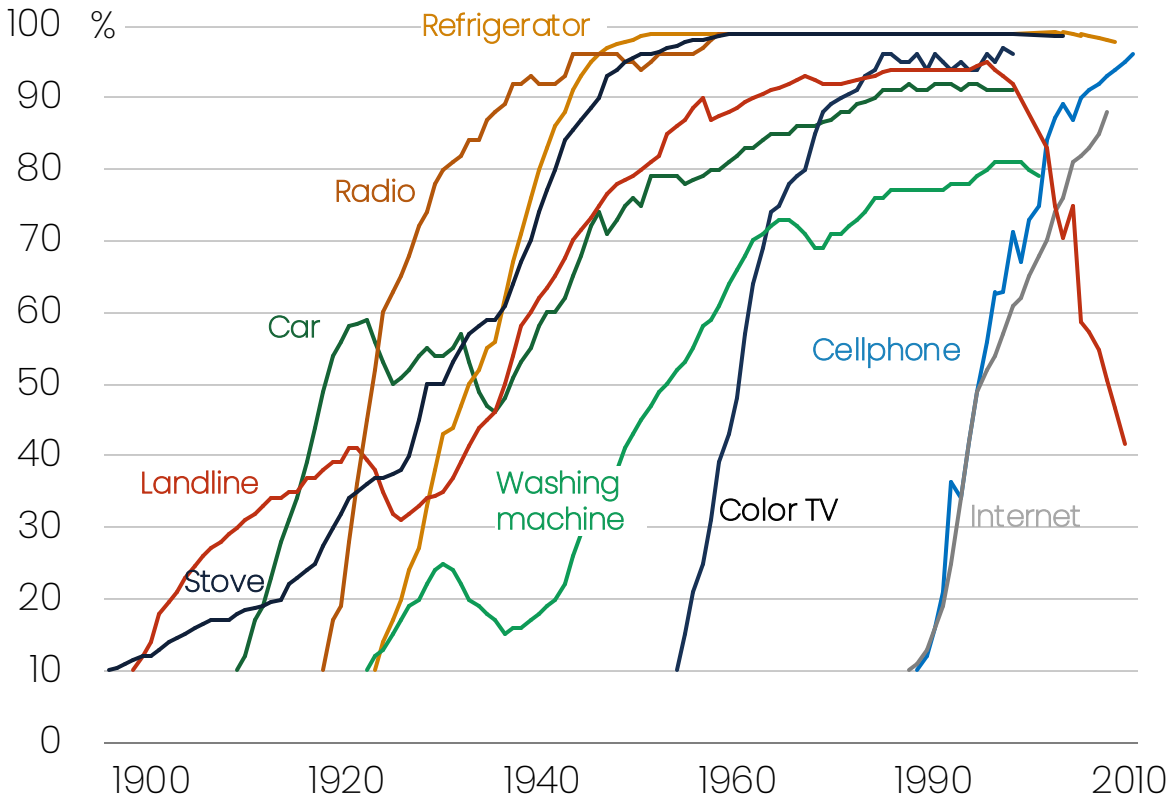
EMBER

S-curve as usual, not business as usual

Successful technologies grow along S-curves

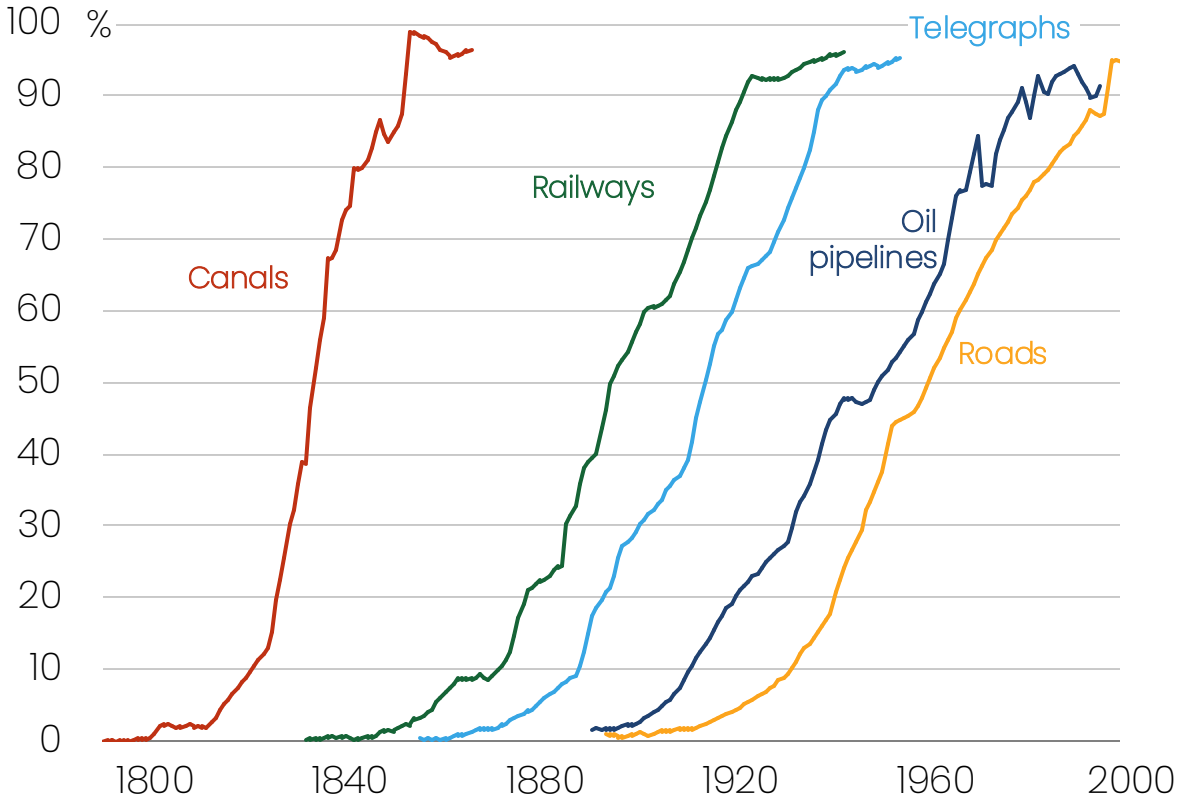
Individual products

Technological adoption by household in the United States



Infrastructure systems

Share of maximum size in the United States



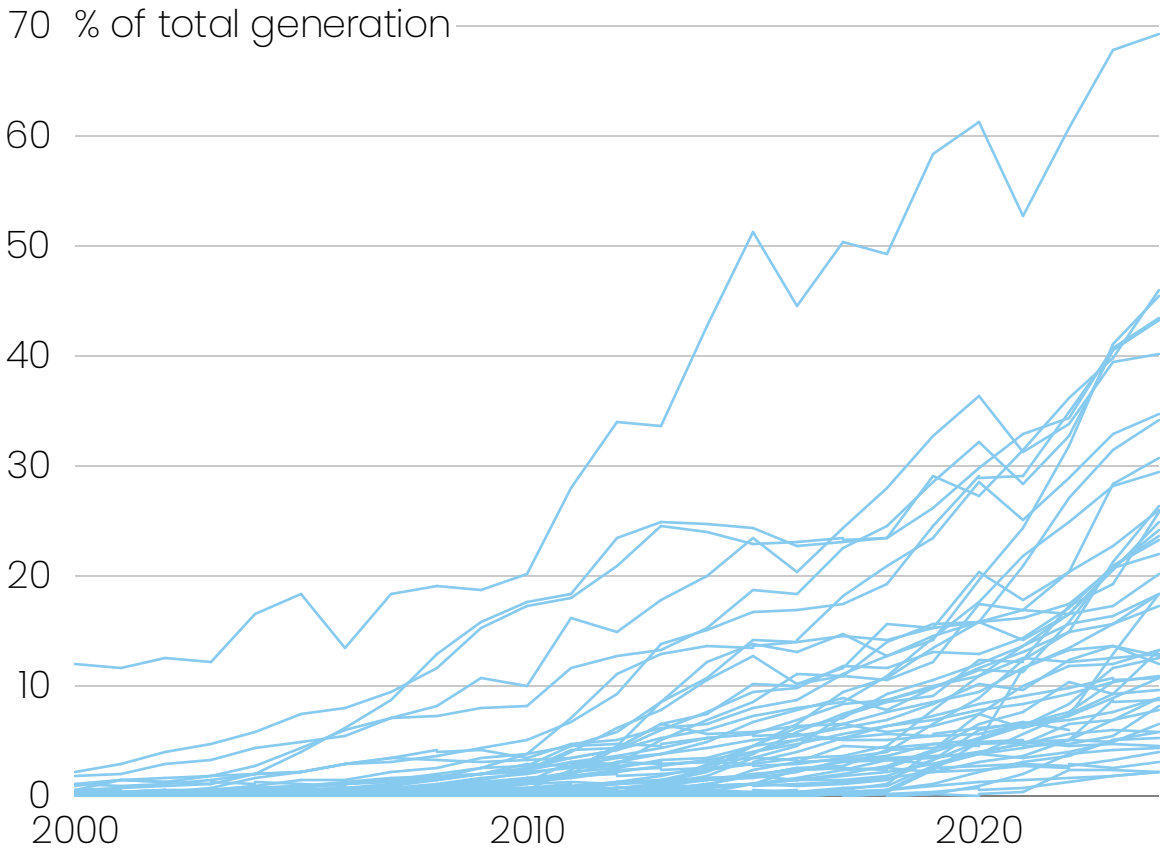
Sources: Comin & Hobijn via OWID, Grubler, RMI.

EMBER

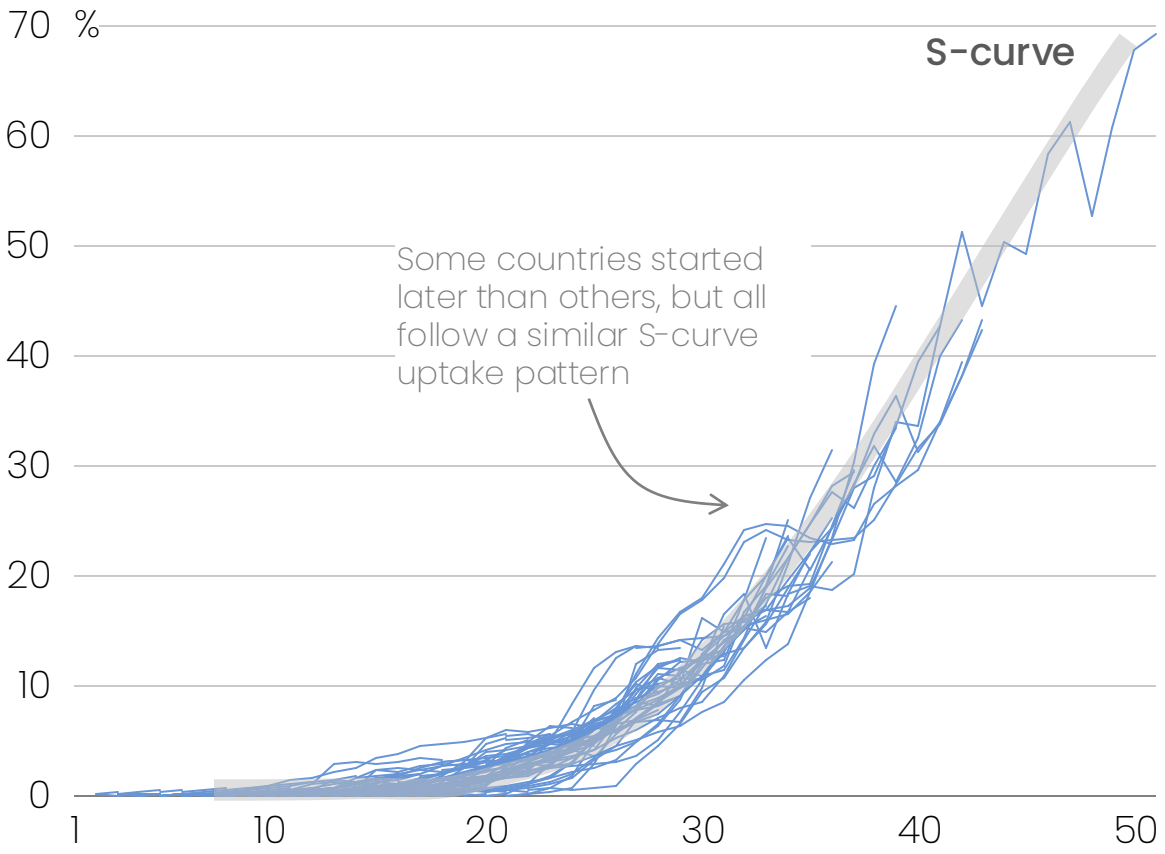
S-curves are the signal in the noise

Electrotech is growing on S-curves; timing varies but the shape is surprisingly uniform

Solar and wind uptake by country – actual



Solar and wind uptake by country – time-shifted



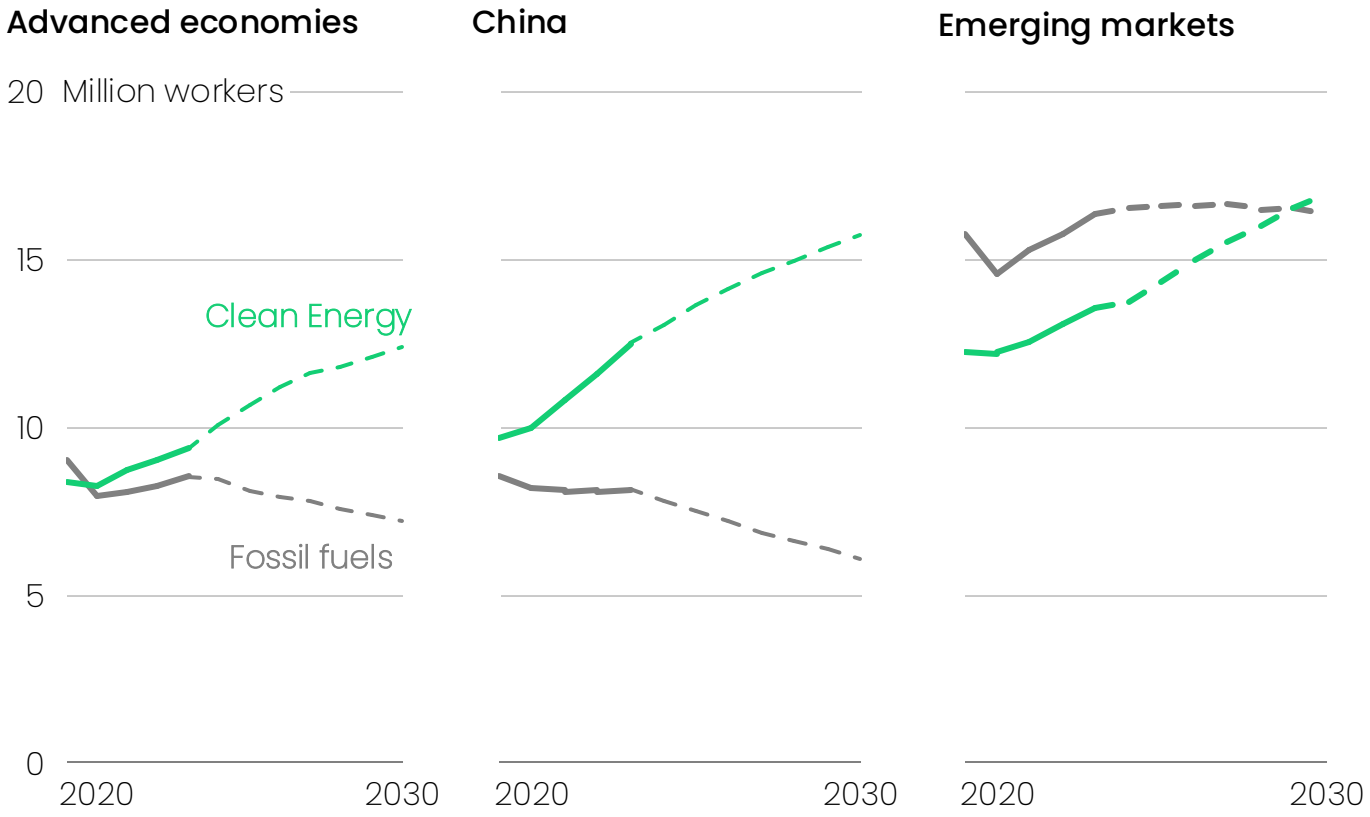
Sources: Ember data & analysis. Note: Based on the 75 largest economies by electricity demand, filtered by countries with >2% of generation from solar and wind (N=52). Country solar & wind shares were time-shifted to a global logistic S-curve.

EMBER

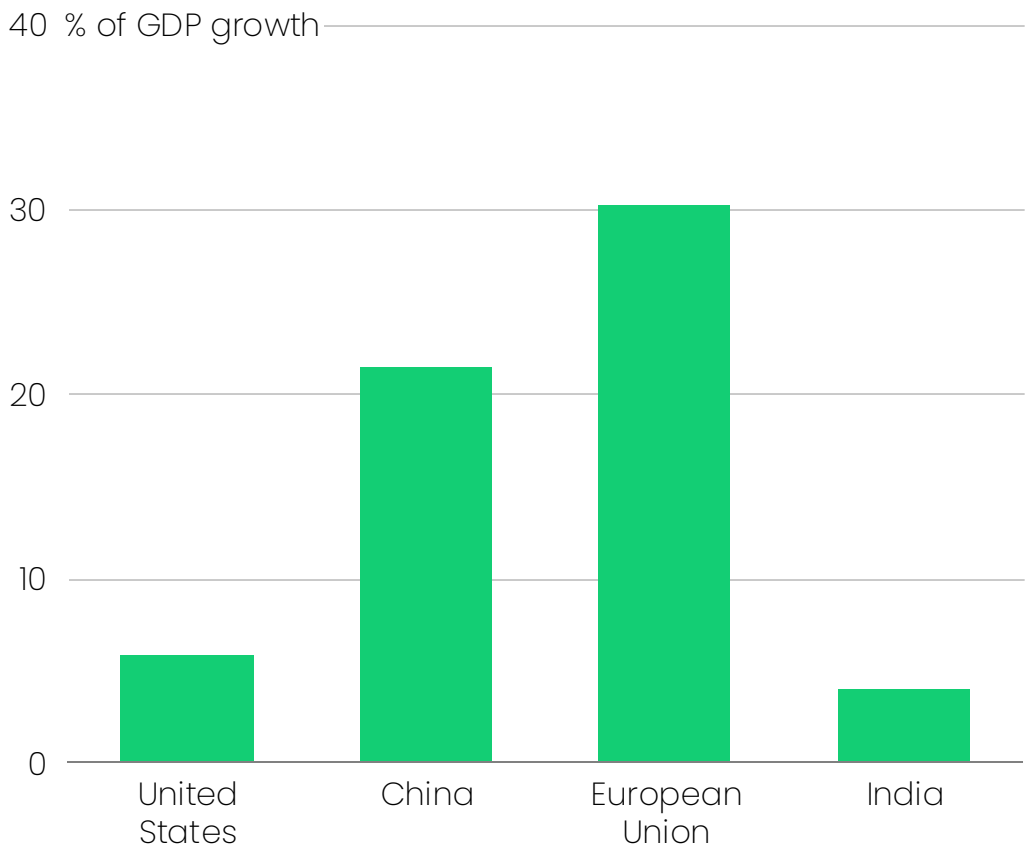
To the victor go the spoils

Winning at electrotech means gaining cheap energy, jobs, growth, and future industries

Change in energy employment, 2019-2030



Contribution of cleantech to GDP growth, 2023



Sources: IEA World Energy Employment 2024 for STEPS scenario (I), IEA ETP

EMBER

Chapter 4.3
The geopolitics of change

01

Fossil fuels create dependency and risk

Fossil fuels are burnt every day and have to be bought again the next day, creating system risks for the buyers. Three quarters of the world live in fossil fuel importers, and regions like Europe are dependent on imported fossils for two thirds of their energy supply. In a world or rising tension, that is far too much risk to bear.

02

Electrotech enables energy security

Electrotech is the foundation of energy security because every country has access to the sun and wind, and can electrify end demand. Renewables added to the electrification of transport and low temperature heat can reduce fossil imports by 70%. Once electrotech is bought, it lasts for decades, providing insulation from the vagaries of global pricing.

03

China is leading the race to the top

China is leading the electrotech revolution and deploying its technology at scale and speed into the emerging markets. Other countries seeking independence and influence will need to compete in this race to the top for the superior technologies of the future.

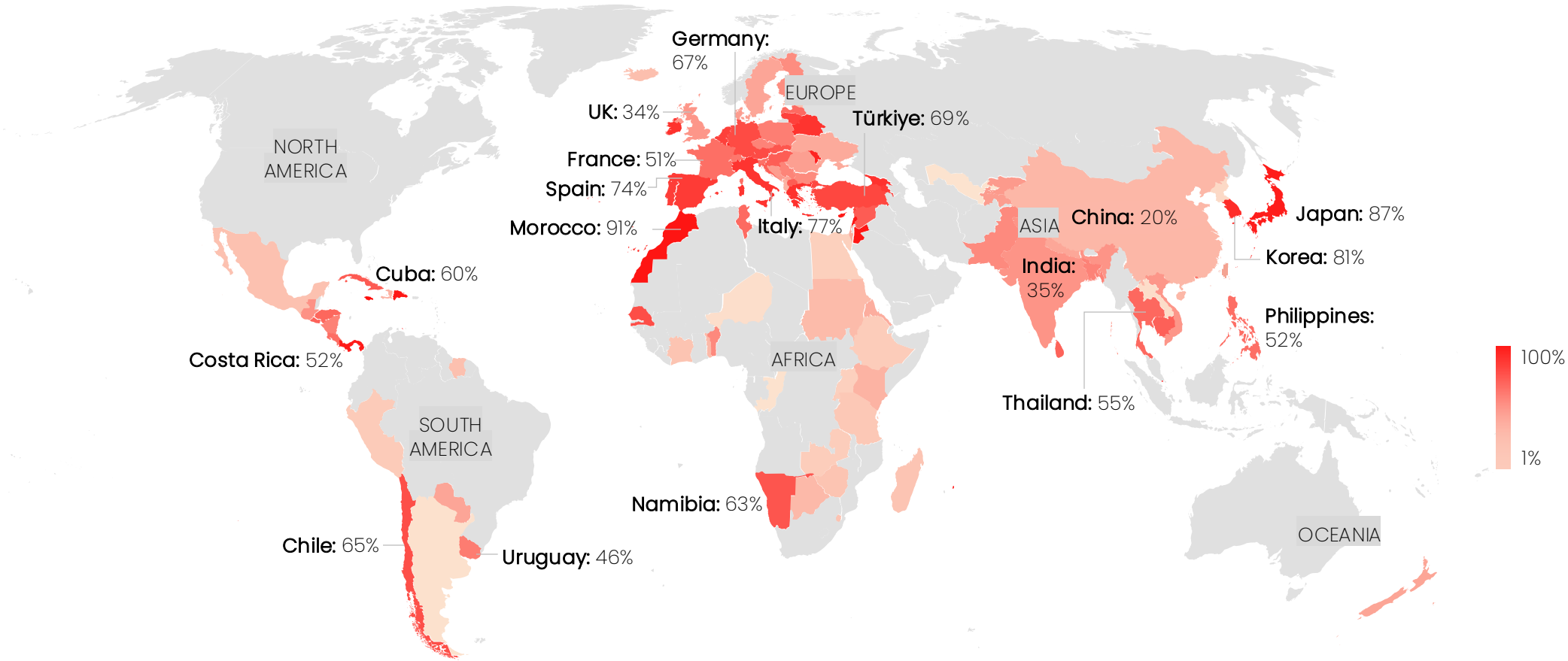
>> Return to Table of Contents

EMBER

Fossil import dependency is widespread

Over 50 countries import more than half their primary energy as fossil fuels

Fossil net imports as a share of primary energy demand 2022, %



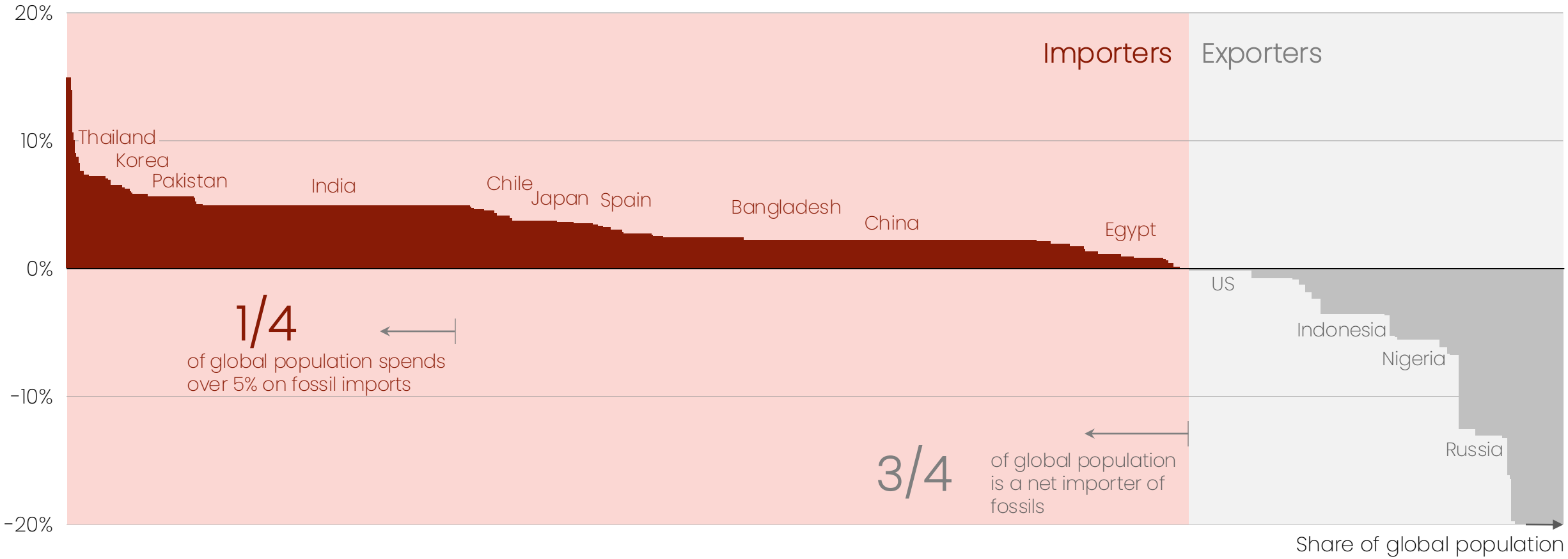
Sources: IEA WEB, Ember analysis. Map boundaries are from Microsoft Bing and do not imply any judgment on legal status or sovereignty.

EMBER

Fossil fuel imports are very expensive

A quarter of the world spends over 5% of GDP on annual fossil fuel imports

Fossil fuel net imports (-) and exports (+) value as share of GDP, 2022



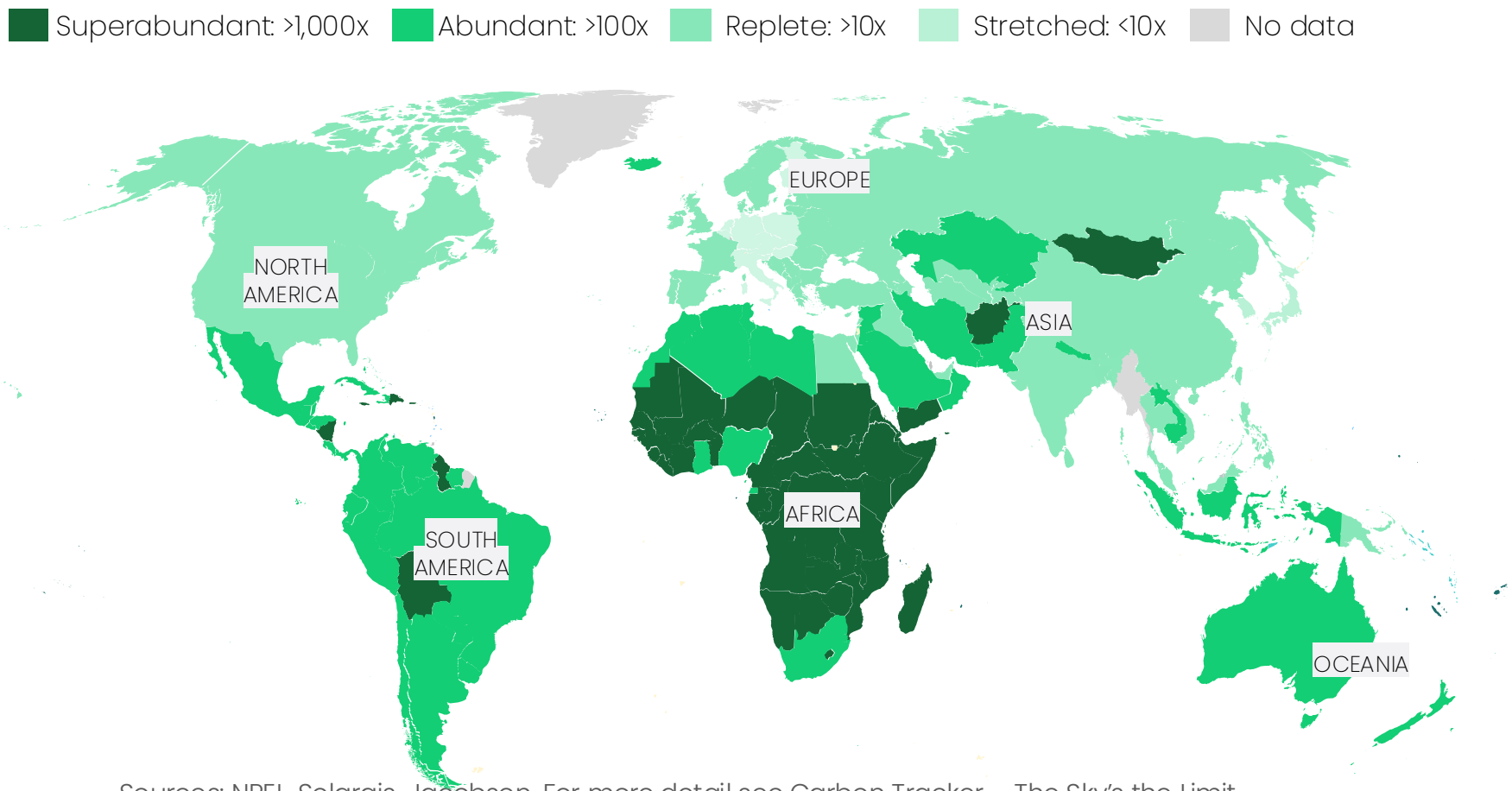
Note: GDP balance based on energy trade balances in EJ from 2022, multiplied by typical commodity prices from IEA.
Sources: IEA WEB, Ember analysis. • Note 1: the y-axis is capped at -20% for readability.

EMBER

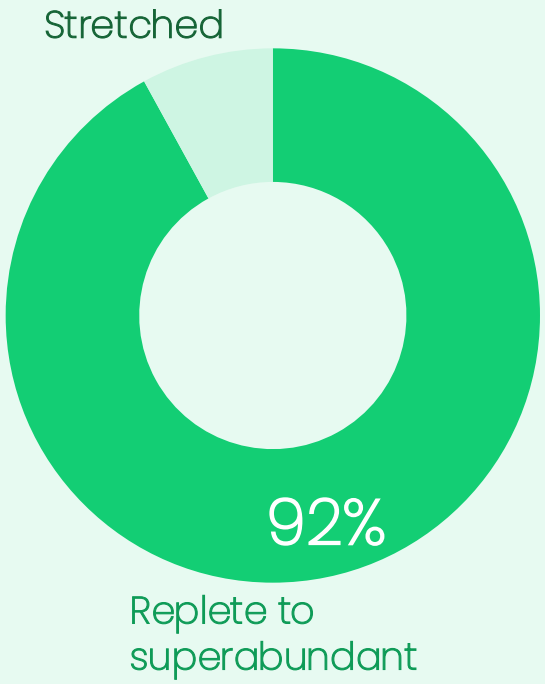
Renewables are available to all

They are 100x bigger than fossil fuels and every country has enough to be self-sufficient

Renewable potential as a multiple of energy demand in 2022



Share of population endowed with replete or better renewable resource



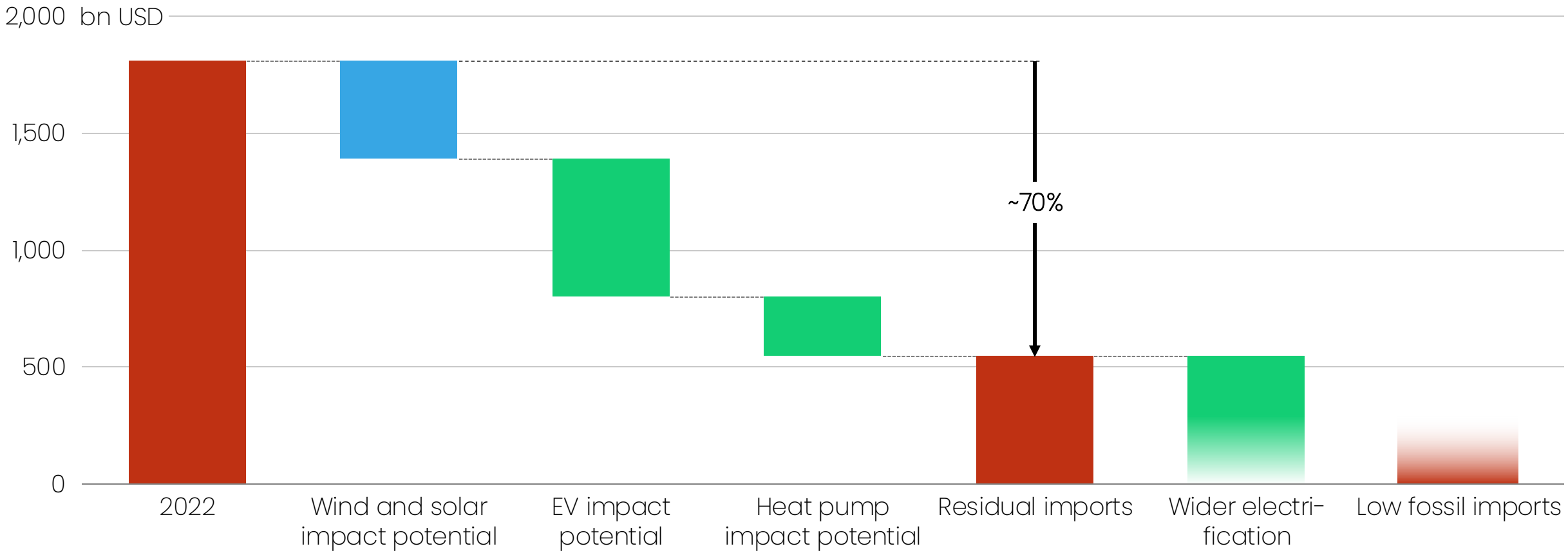
Sources: NREL, Solargis, Jacobson. For more detail see Carbon Tracker – The Sky's the Limit
Map boundaries are from Microsoft Bing and do not imply any judgment on legal status or sovereignty.

EMBER

Renewables, EVs and heat pumps set you free

Just a few technologies can reduce global energy imports by 70%

Global net spending on fossil fuels by importers



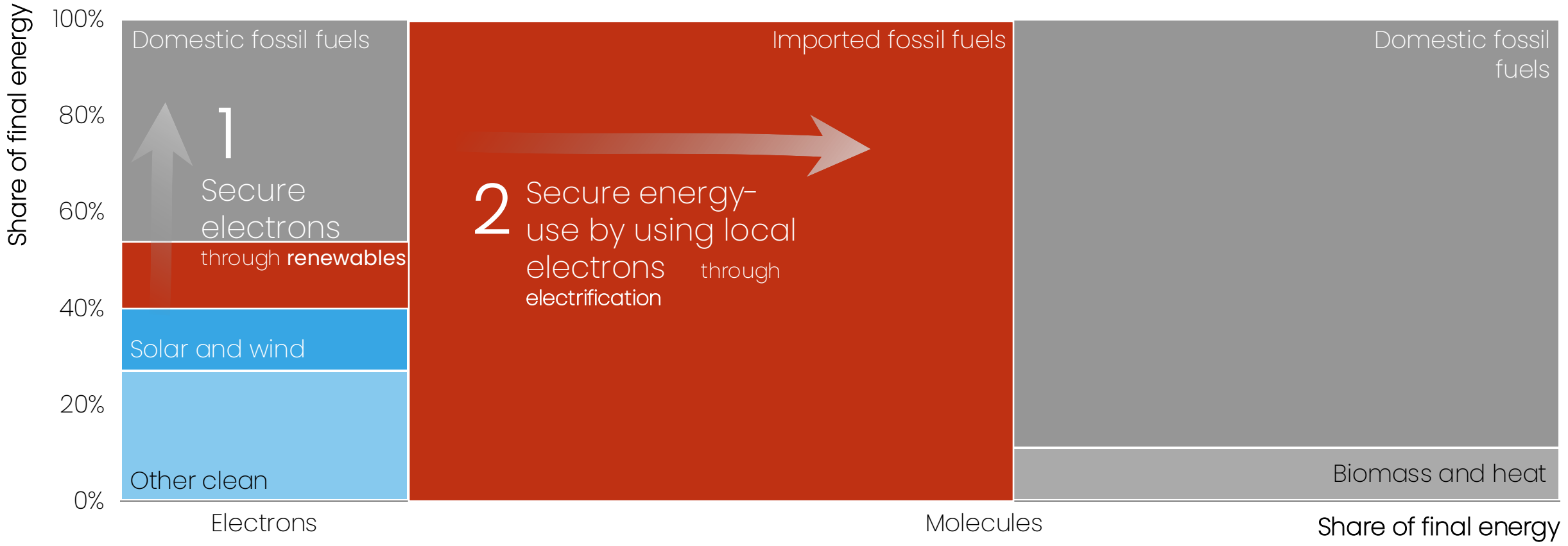
Sources: IEA WEB, World Bank, Ember - Energy Security in an insecure world. The chart illustrates the reduction in fossil fuel imports possible by deploying solar, wind, electric vehicles and heat pumps

EMBER

Electrotech brings energy security

More domestic renewables and electrification can drastically curb energy dependence

Global energy demand in 2023

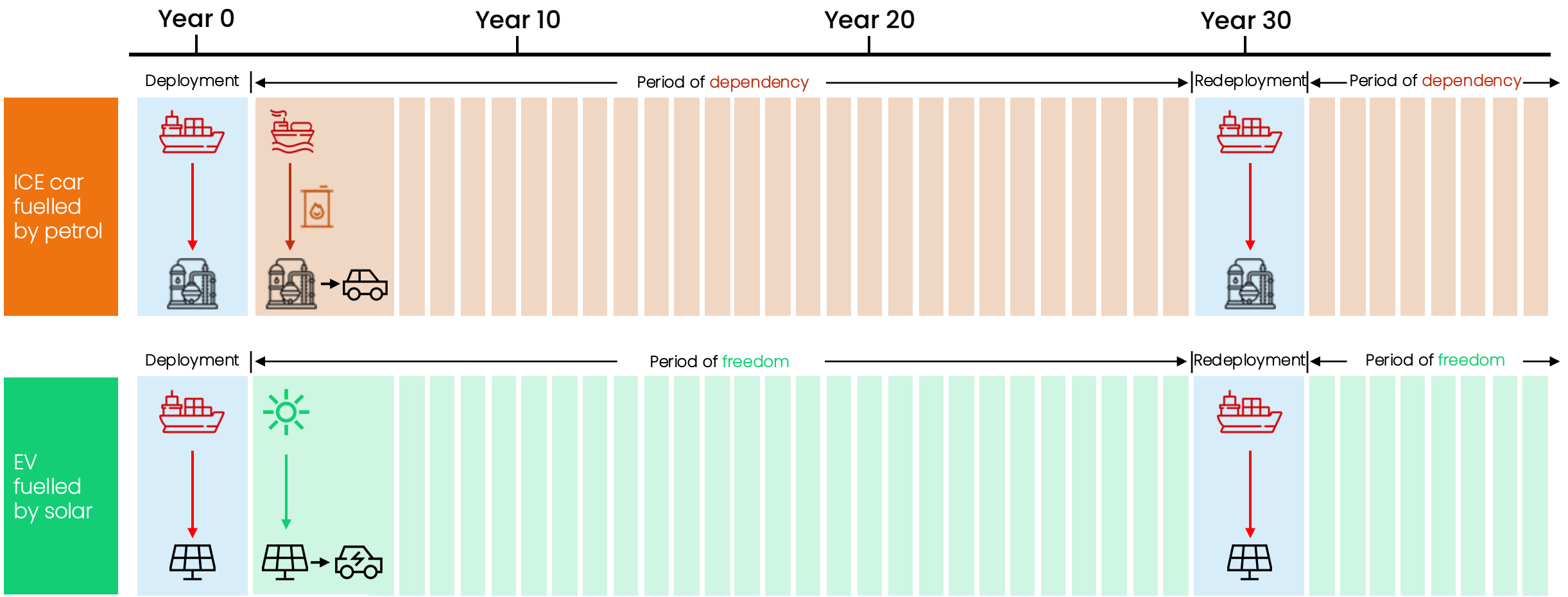


Sources: IEA WEO 2024, IEA WEB, Ember • Notes: In gross terms and in final EJ. Other clean electrons are mainly hydro and nuclear.

EMBER

You can’t turn off the sun

A solar panel provides 30 years of energy freedom



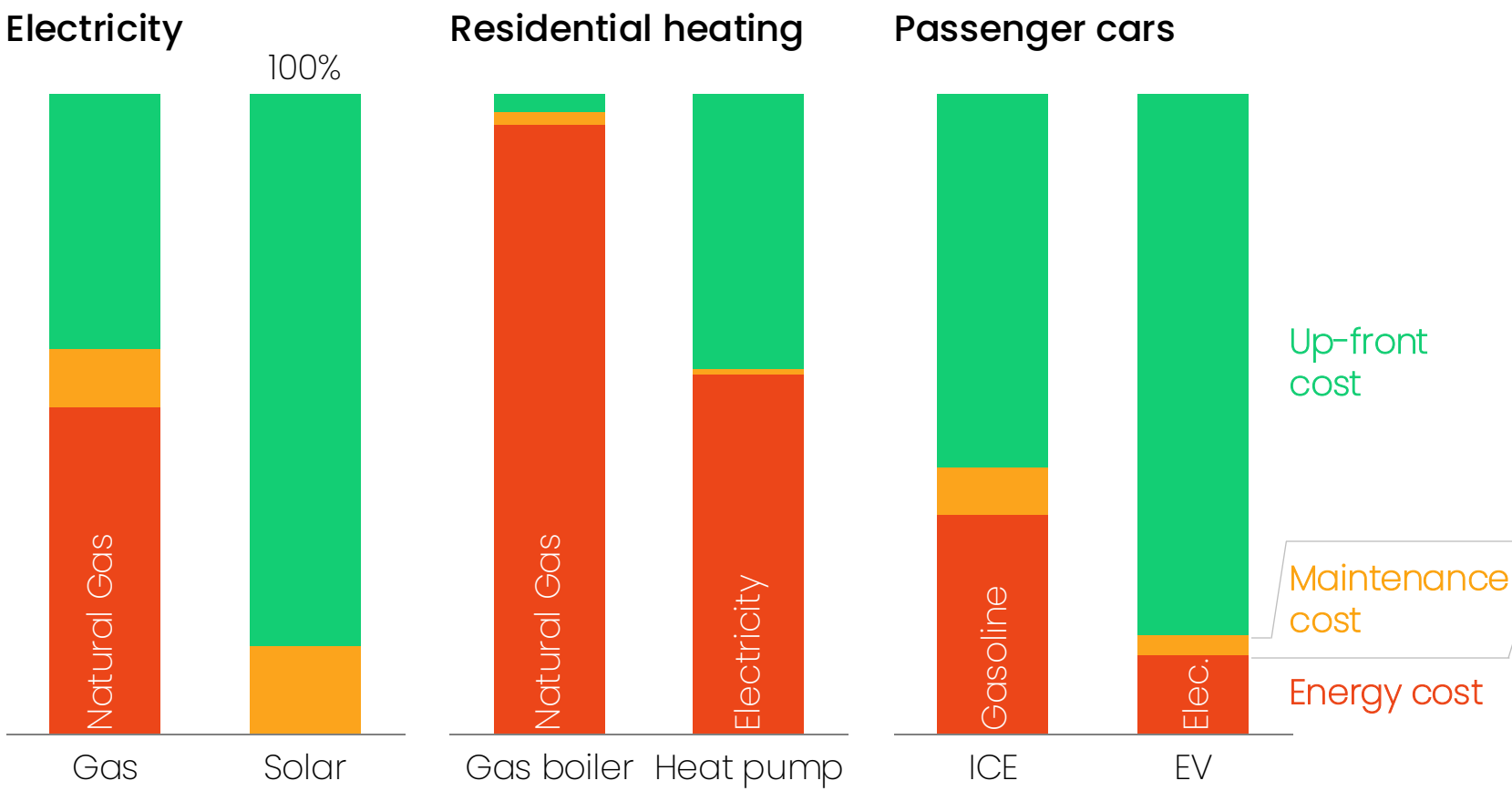
Sources: Ember

EMBER

Electrotech saves you from fossil volatility

Once installed, electrotech costs remain stable — even if global supply chains falter or fuel costs rise

Total cost of ownership breakdown, %, US examples



Inflation risk after deployment

Low/ None — Cost already sunk
Cost don't change with inflation as technology is already deployed.

Mid — Labor & manufacturing inflation
Inflation in labor and replacement parts can raise maintenance cost.

High — Energy inflation
Note: This applies less to electricity, as purchased electricity can originate from renewables like solar power, which primarily involve fixed costs and therefore carry minimal inflation risk.

Sources: Lazard 2024; NREL; IEA EV TCO tool; RMI analysis

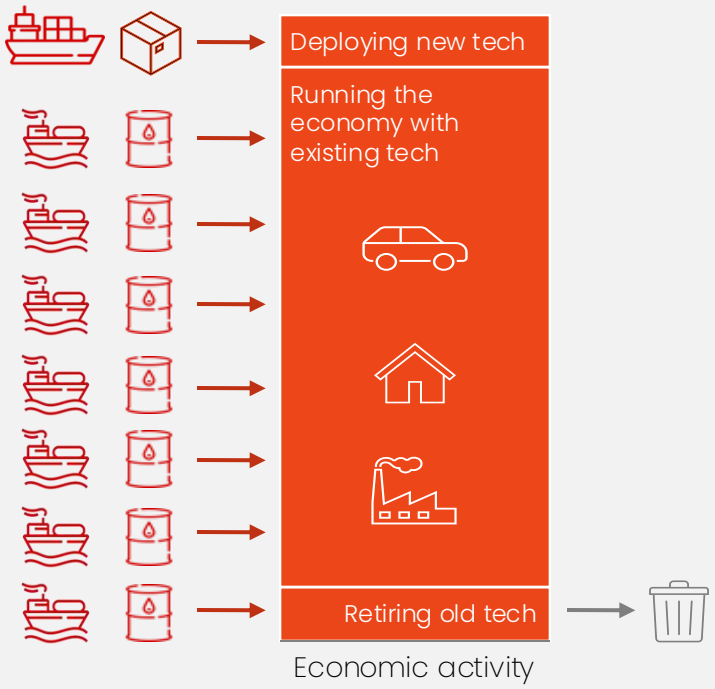
EMBER

Electrotech offers a path to permanent energy security

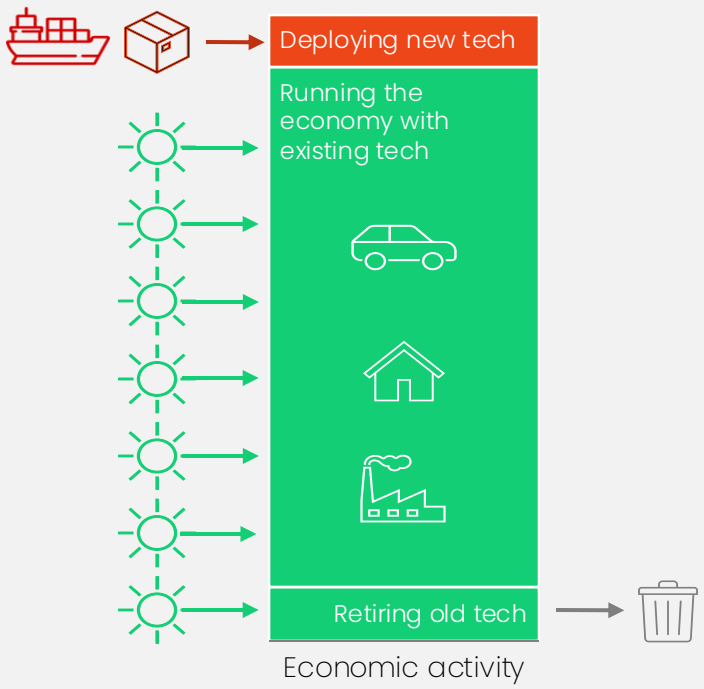
When fossil flows stop, the economy stops. When electrotech flows stop, only growth is at risk

From fossil import dependency... → **...to electrotech import dependency...** → **...to full circular energy independence.**

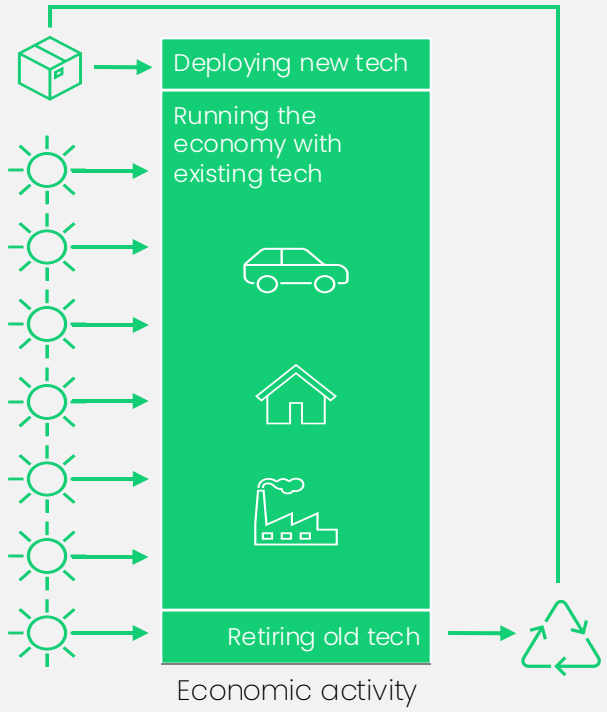
In an economy running on fossil imports, **when imports stop, all activity stops**



In an economy running on imported electrotech, **when imports stop, only growth is inhibited.**



In an economy running on local circular electrotech, **trade shocks have little impact**



At immediate risks without imports

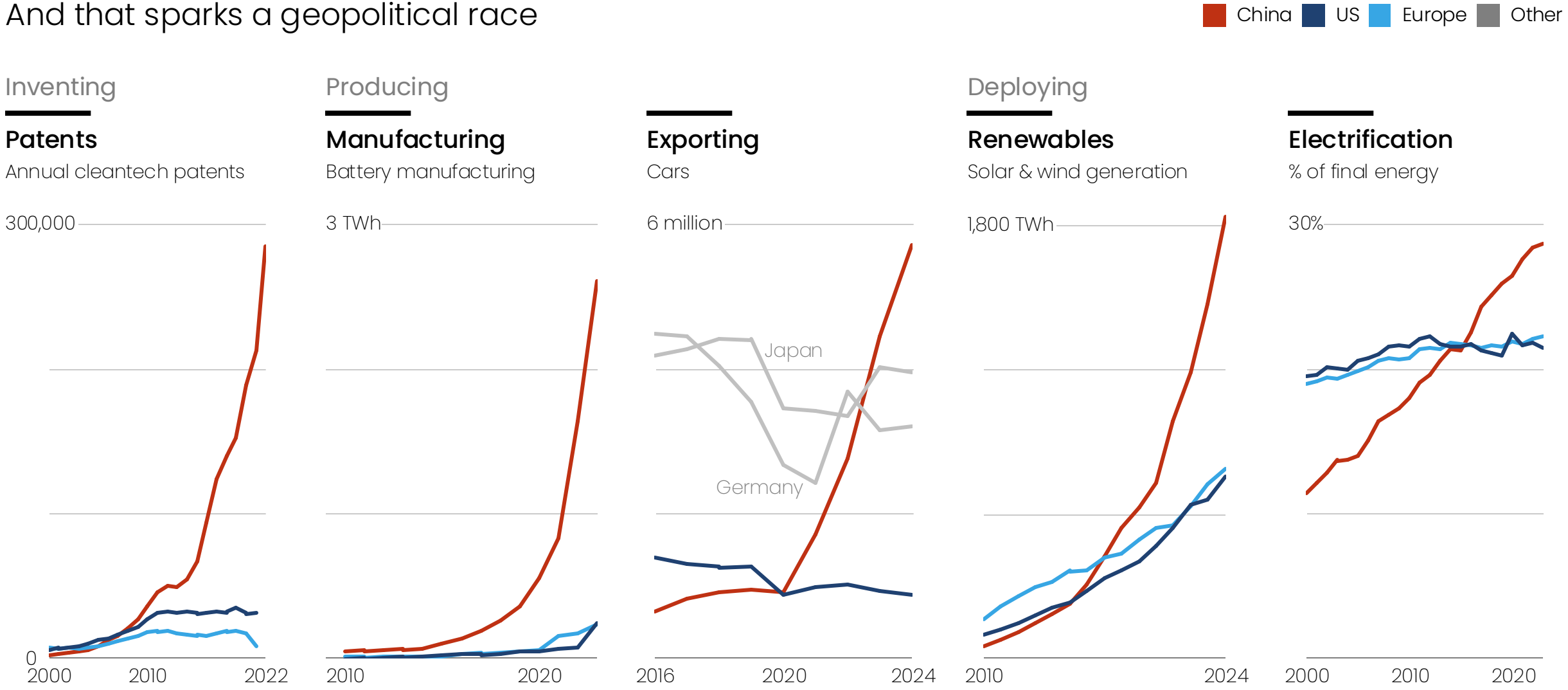
Not at immediate risk

Sources: Ember• Note: bar sizes are illustrative

EMBER

China is the first major electrostate

And that sparks a geopolitical race



Sources: Ember, IEA WEB, IRENA, BNEF, NYT.

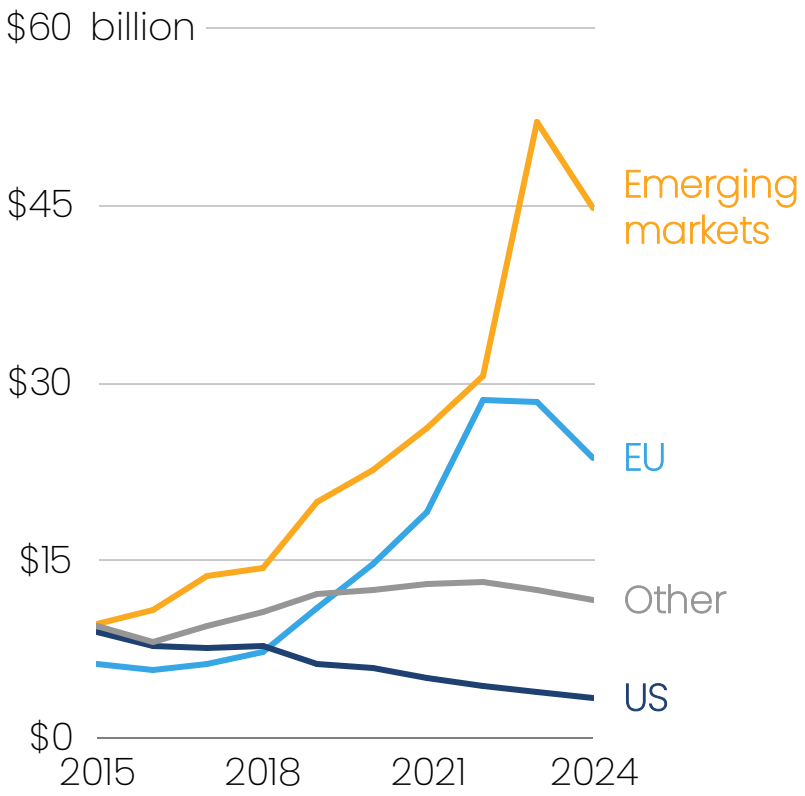
EMBER

China is exporting the electrotech revolution to the world

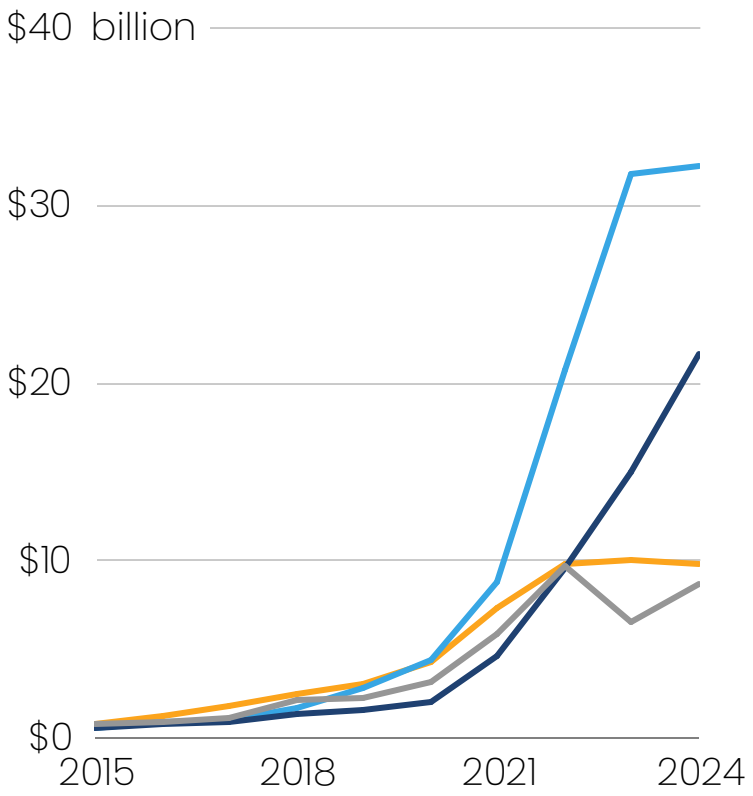
Gaining allies along the way — especially in the emerging markets

Chinese exports

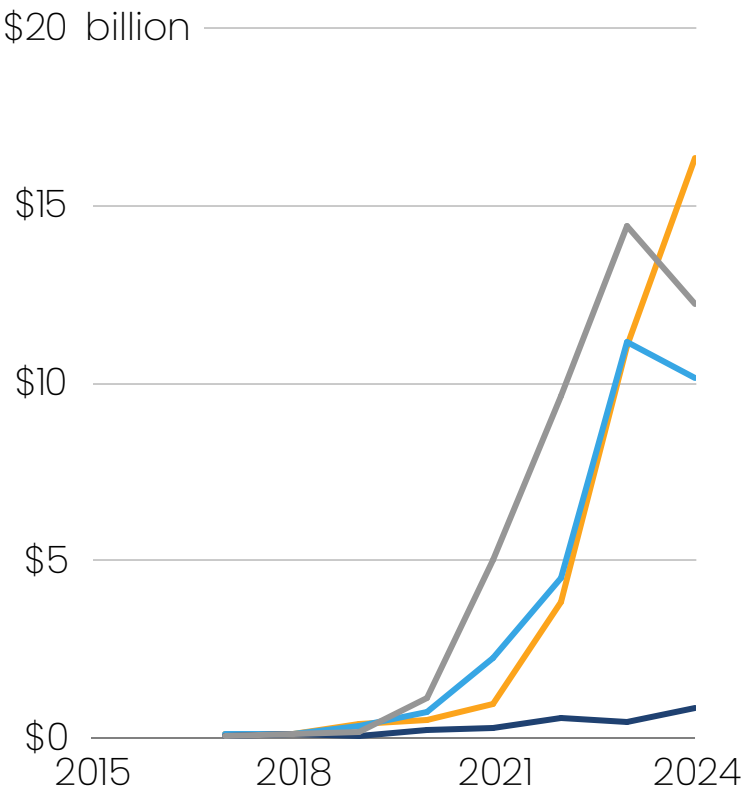
Solar PV



Batteries



Electric vehicles



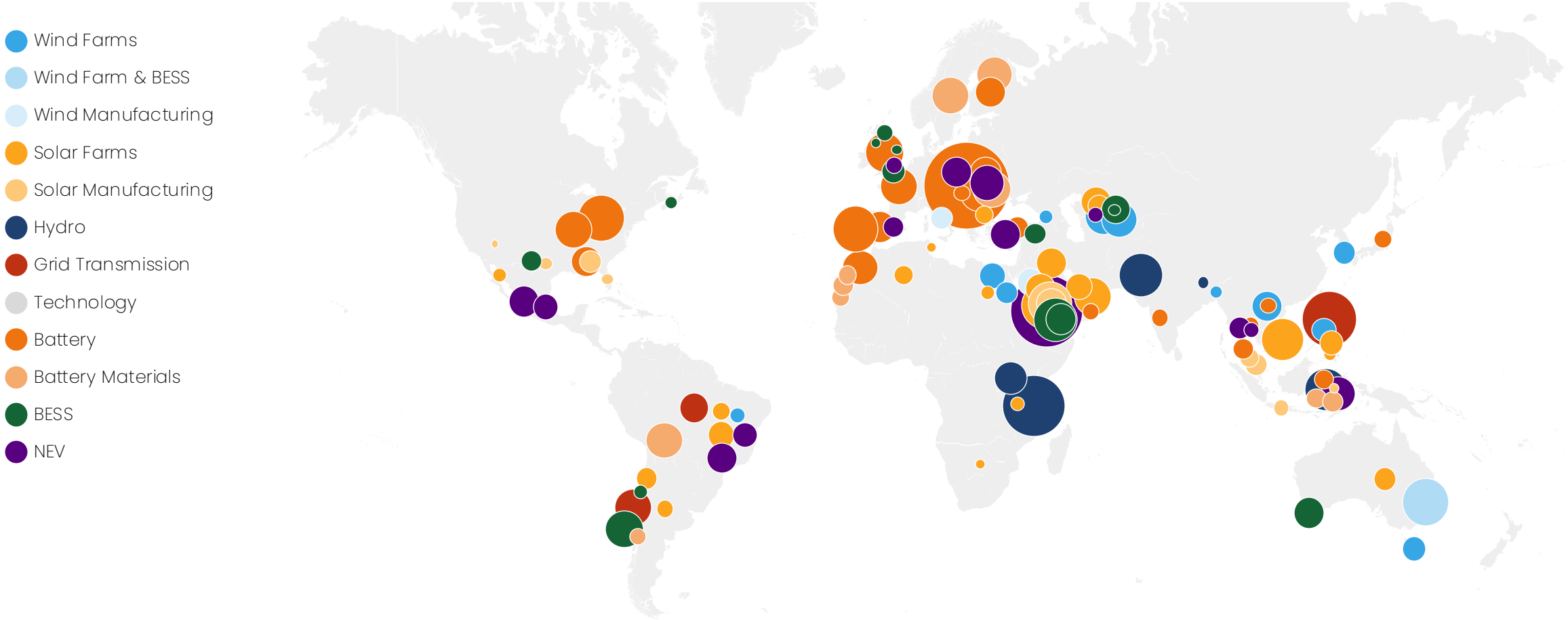
Sources: Comtrade; Dialogue Earth; Nat Bullard

EMBER

China is exporting the capacity to build electrotech

Over $100bn of outbound FDI on electrotech since 2023

Chinese electrotech investment since 2023



Sources: Climate Energy Finance: Power Shift, Ember annotation

EMBER

Chapter 5.1

Profound impact on the energy system

01

Electricity 2.0 speeds up change

Electrotech solutions are converging into a river of change which will drive more rapid electrification and a continuation of the growth of renewables up S curves.

02

The emerging market leapfrog continues

The emerging markets will continue their energy leapfrog, led by the growth nations of Asia. Many emerging markets are deploying renewables more rapidly than developed markets did before them and are electrifying end demand more quickly.

03

Fossil fuel demand will be in decline by 2030

Fossil fuel demand is on a bumpy plateau at present, but the continued rapid growth of electrotech will increasingly push fossil fuels into decline by the end of the decade. This is substitution not addition. And that creates vulnerability for areas such as refining or LNG.

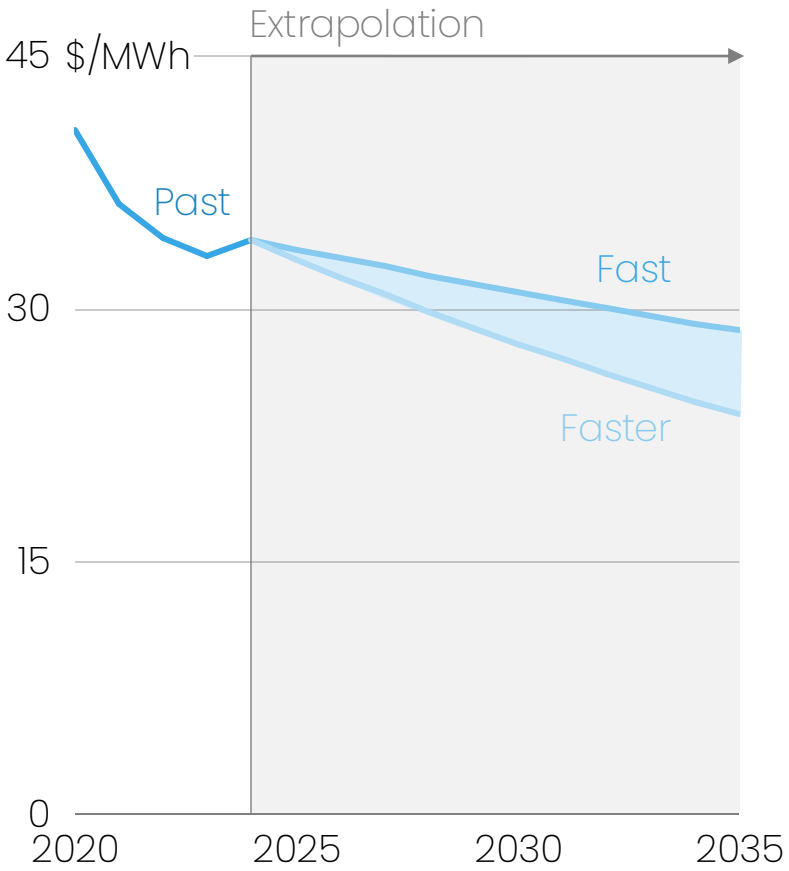
>> Return to Table of Contents

EMBER

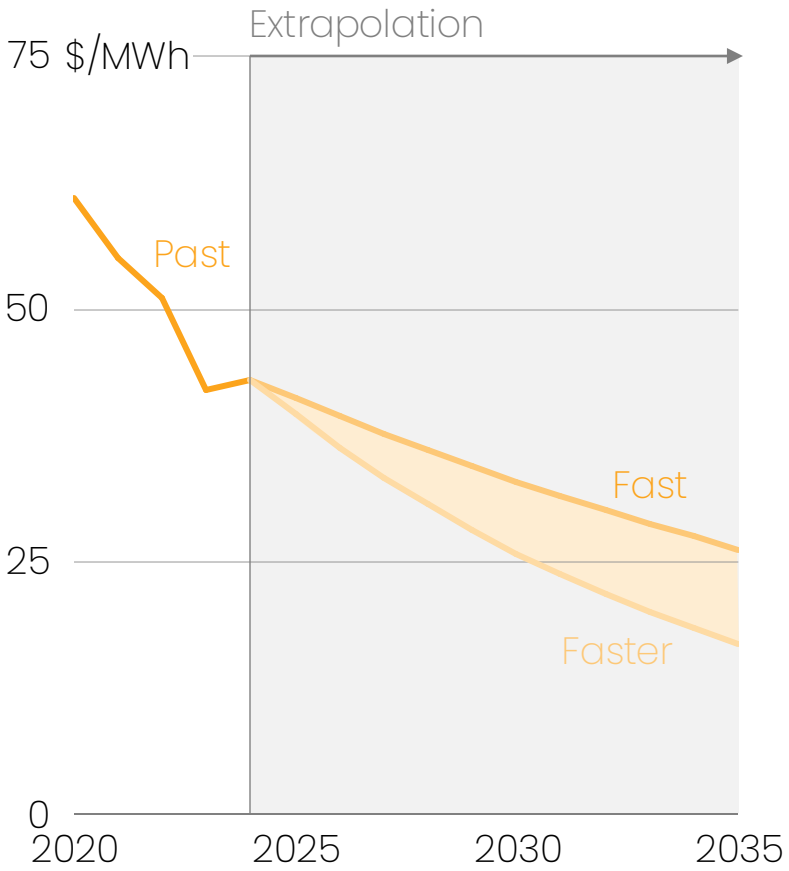
Electrotech will get cheaper driven by learning curves

From competitive to irresistible

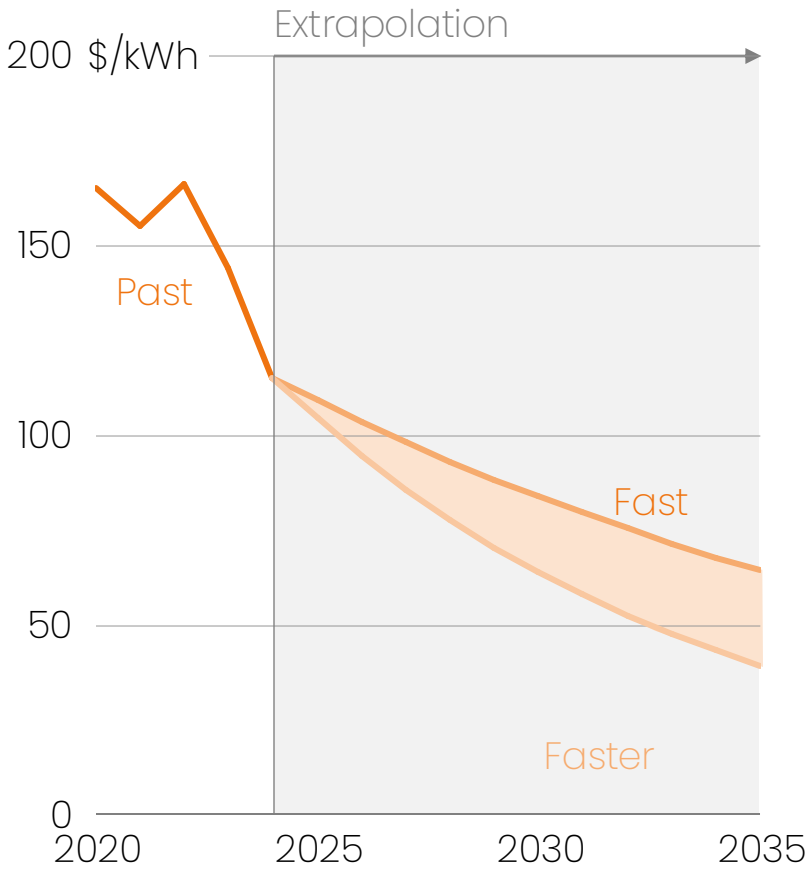
Wind costs



Solar costs



Battery costs

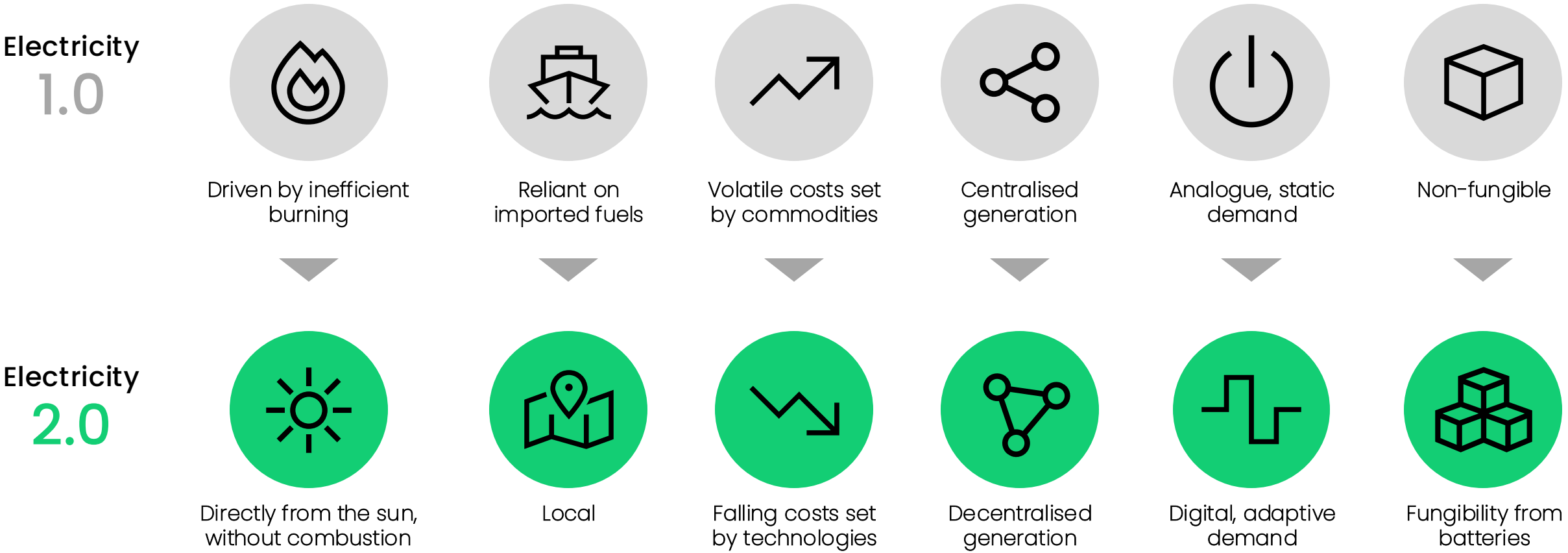


Sources: IRENA, BNEF, Ember Futures extrapolation based on learning rates; a method set out in detail by Oxford INET among others. Costs are derived by extrapolating historic growth rates and learning rates for each of the key technologies for the next decade. Solar assumes growth (g) of 15%-18% and learning rates (LR) of 20-30%. Wind 8-13%(g) growth 12-17% (LR). Batteries 19-22% g & 19-29% LR.

EMBER

Electricity 2.0 is here

Electrification will speed up driven by cheaper, more efficient, local and digital electricity

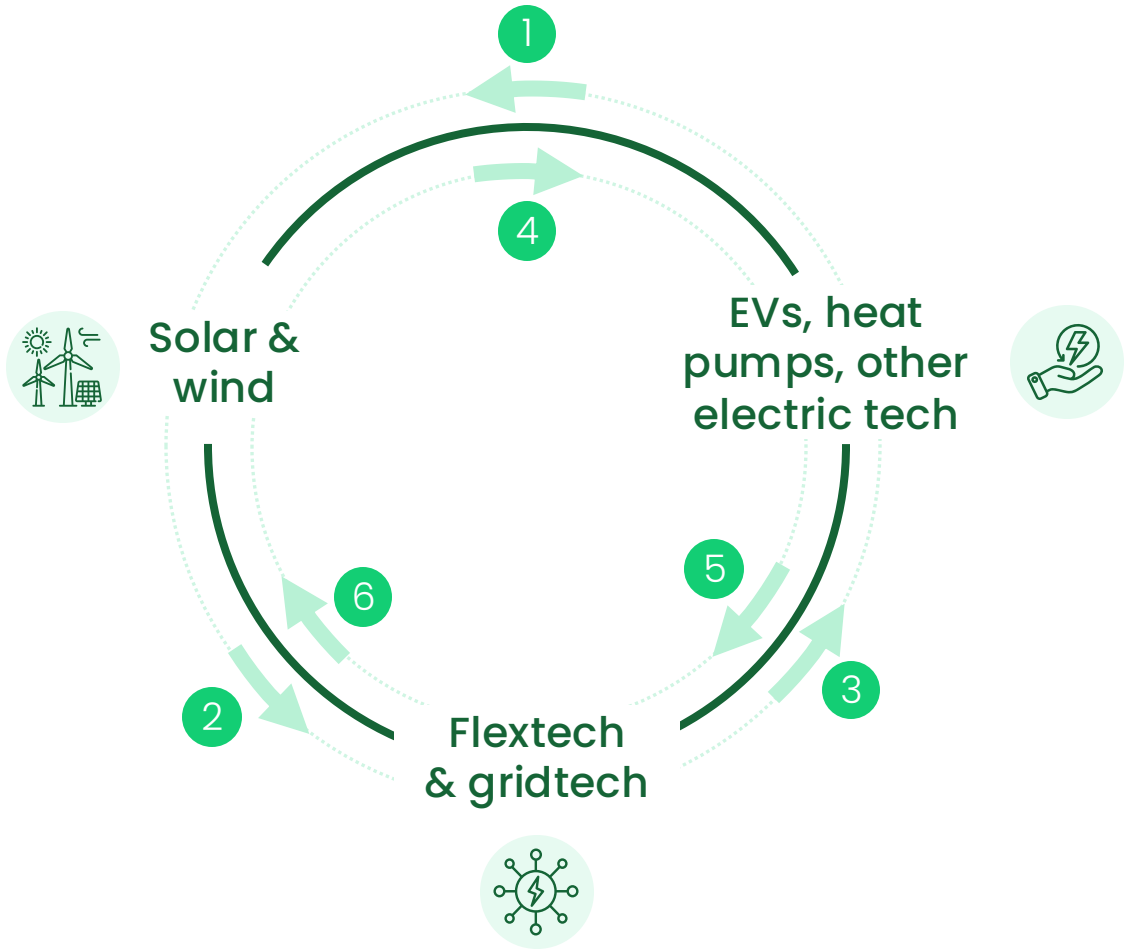


Sources: Ember

EMBER

Electrotech unleashes a virtuous spiral

Advances in one area make the other areas more attractive



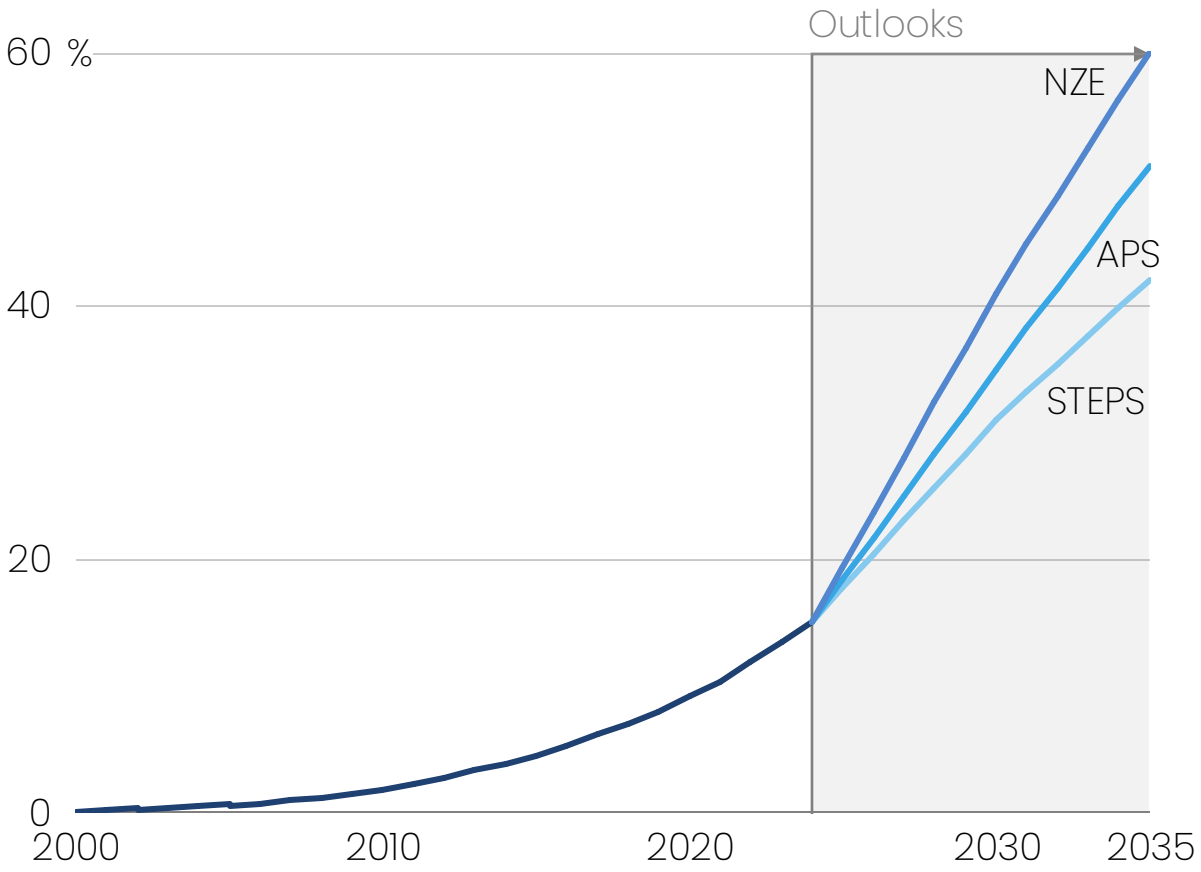
1. Electrified demand scales renewables, driving costs lower
2. Variable renewables need smoothing and create arbitrage opportunities for flextech
3. Using electricity when it's cheapest incentives demand
4. Cheaper, local renewables make electrifying more attractive
5. More demand to pool & optimise
6. Flex & gridtech enable higher penetration

Sources: Ember

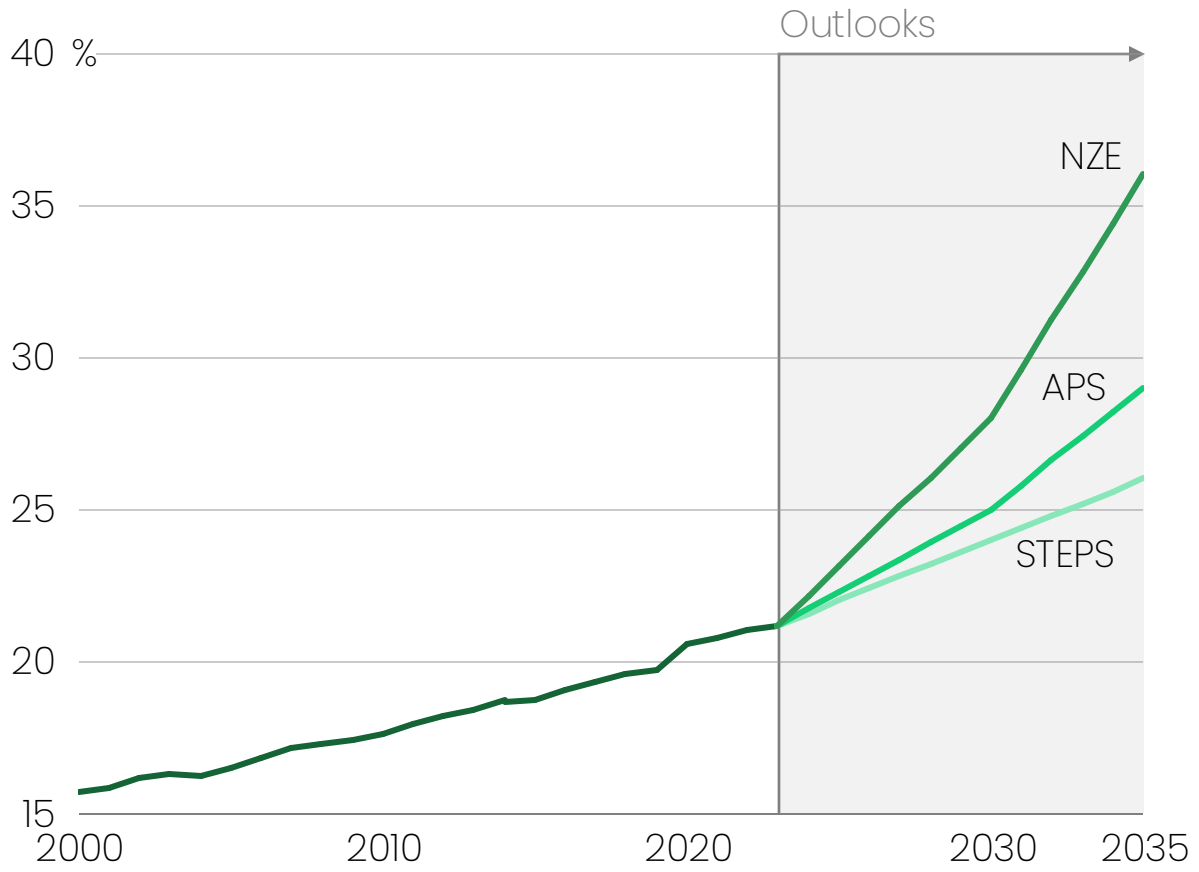
Renewables and electrification will keep growing

The momentum will continue

Solar & wind share of global generation



Electricity share of final energy



Sources: Ember, IEA WEO scenarios. Note NZE stands for (Net Zero), Announced Policies (APS), Stated Policies (STEPS)

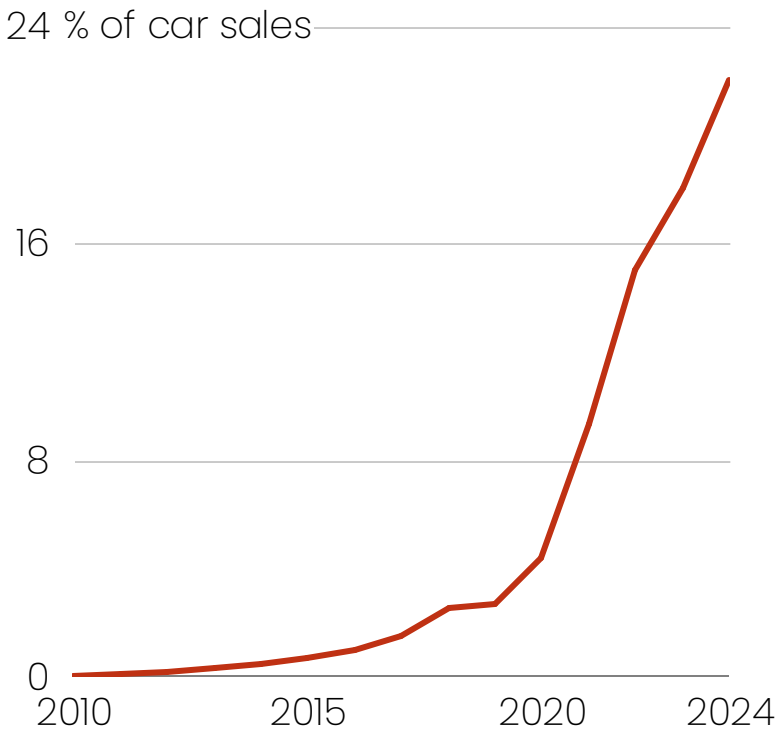
EMBER

Don’t expect the road to be smooth

Global curves are smooth; but locally it is a bumpy ride of lagging and leading

Smooth global curve

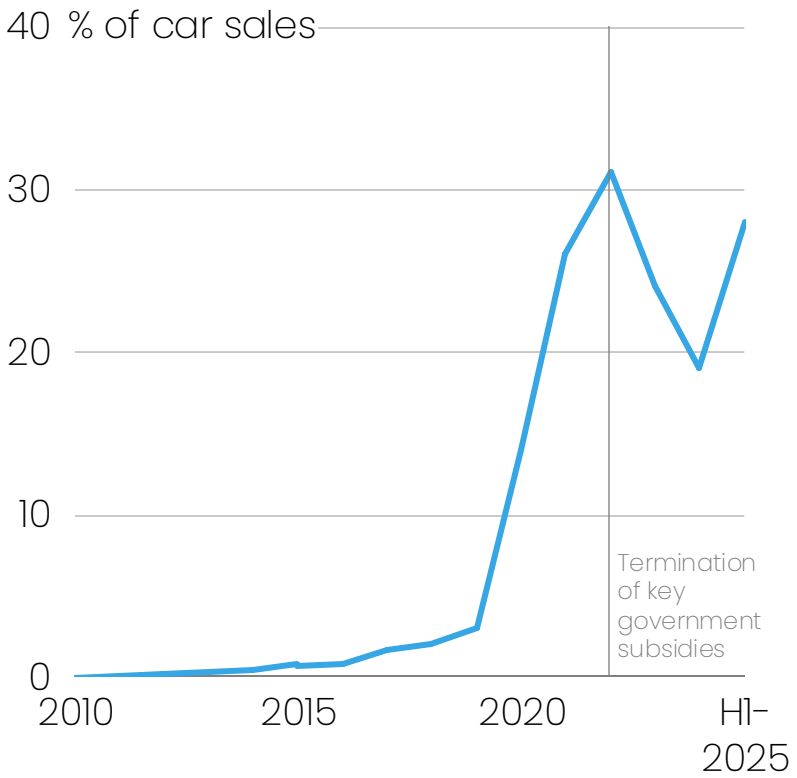
Global EV car sales



Bumpy local curves

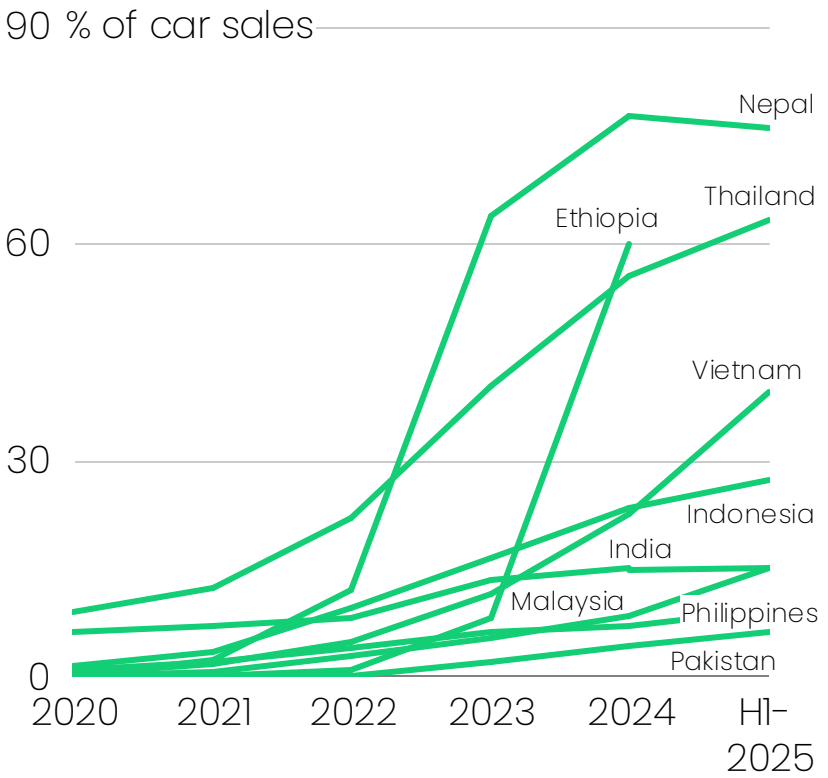
Larger-than-expected slowdown

Germany EV sales



Faster-than-expected acceleration

Emerging market EV sales



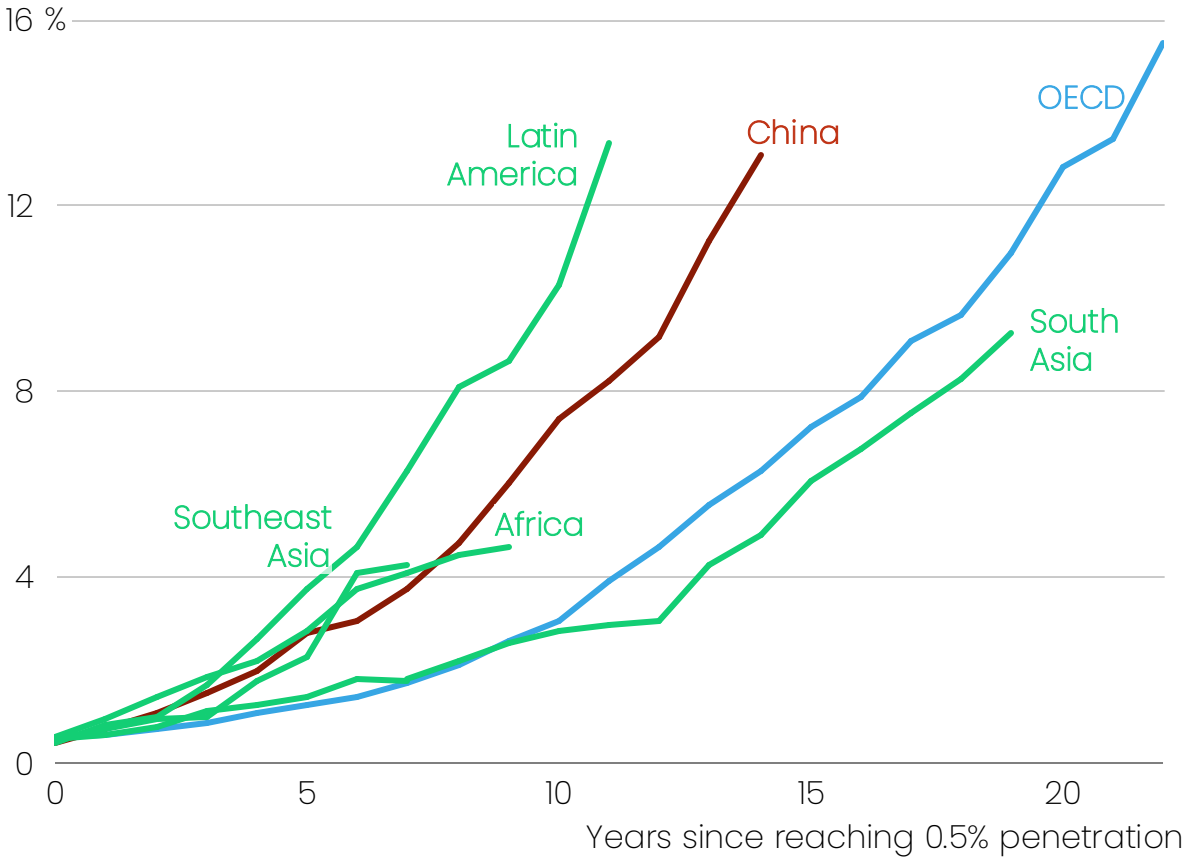
Sources: IEA; Segment Y via New York Times; Ember analysis

EMBER

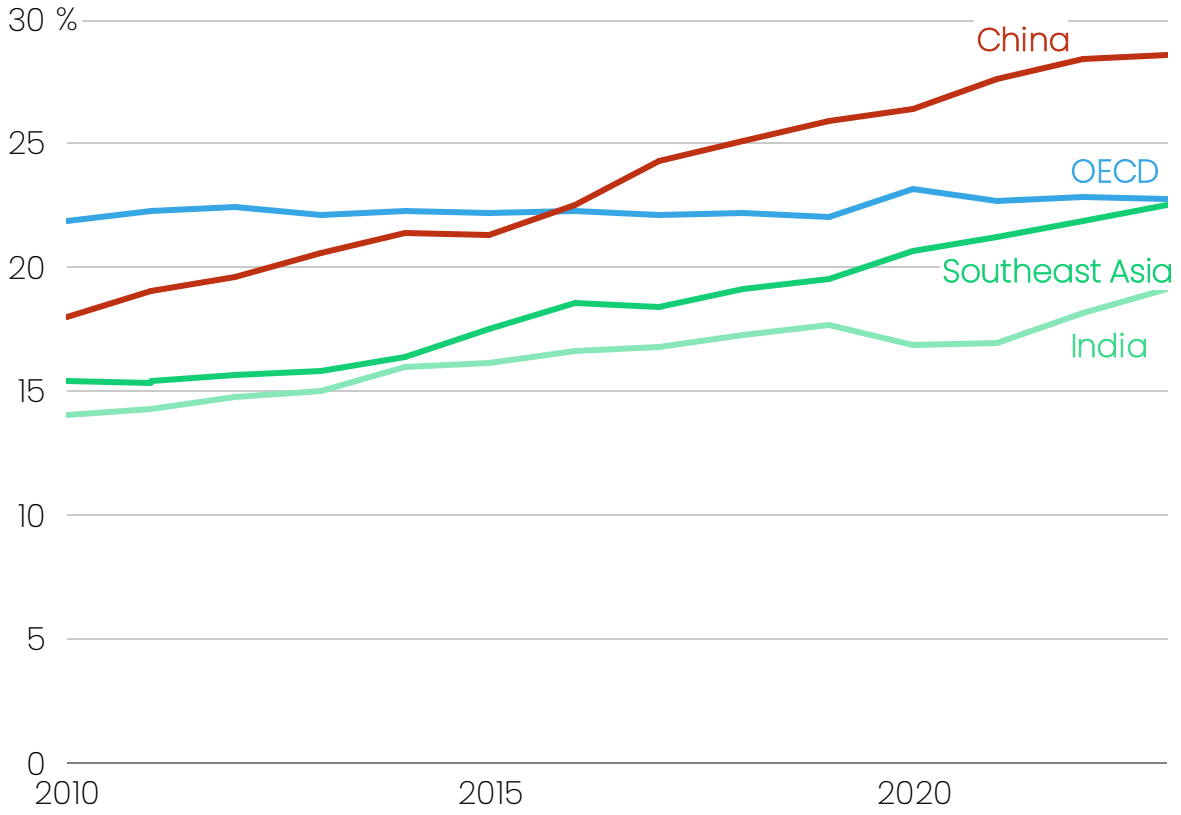
The emerging market leapfrog has strong momentum

Change is happening faster than in the West

Solar & wind share of electricity generation, time-shifted



China and Asia are leapfrogging the OECD in electrification



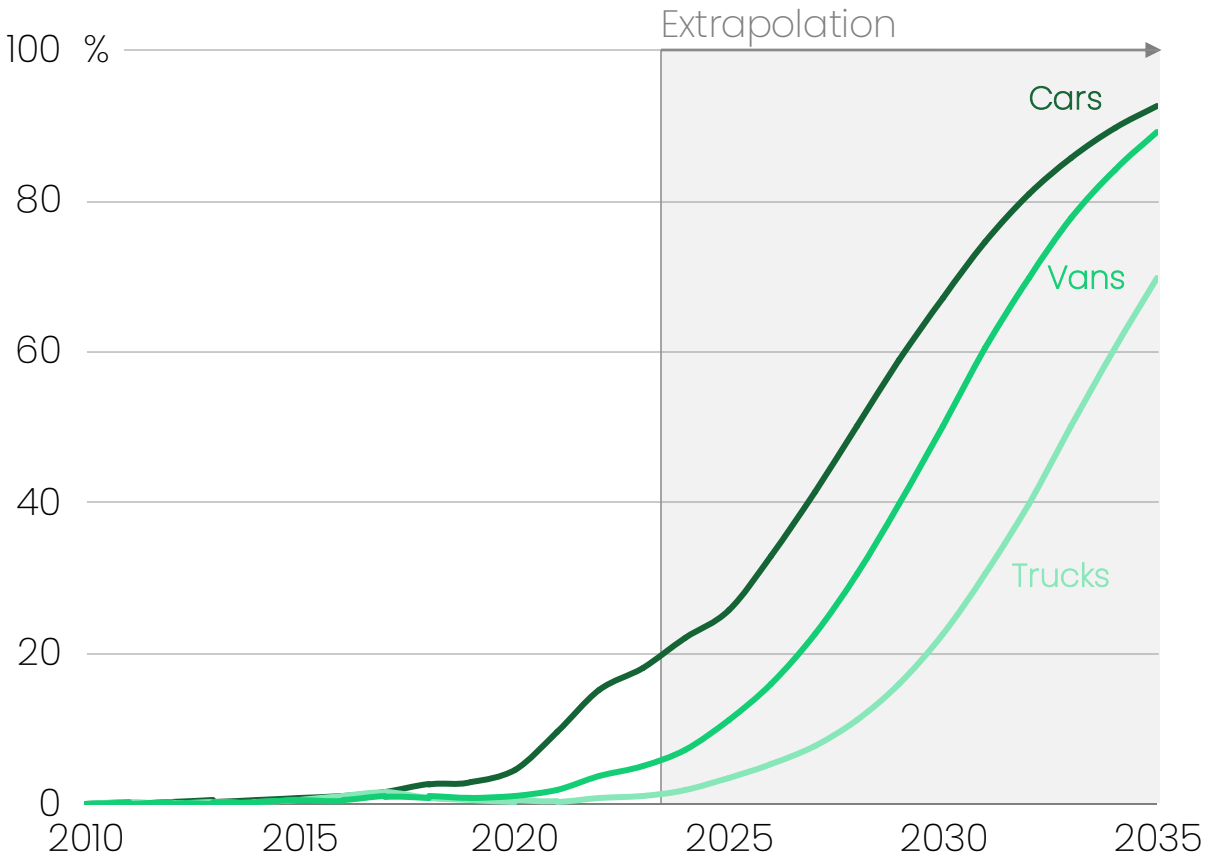
Sources: IEA, RMI, Ember

EMBER

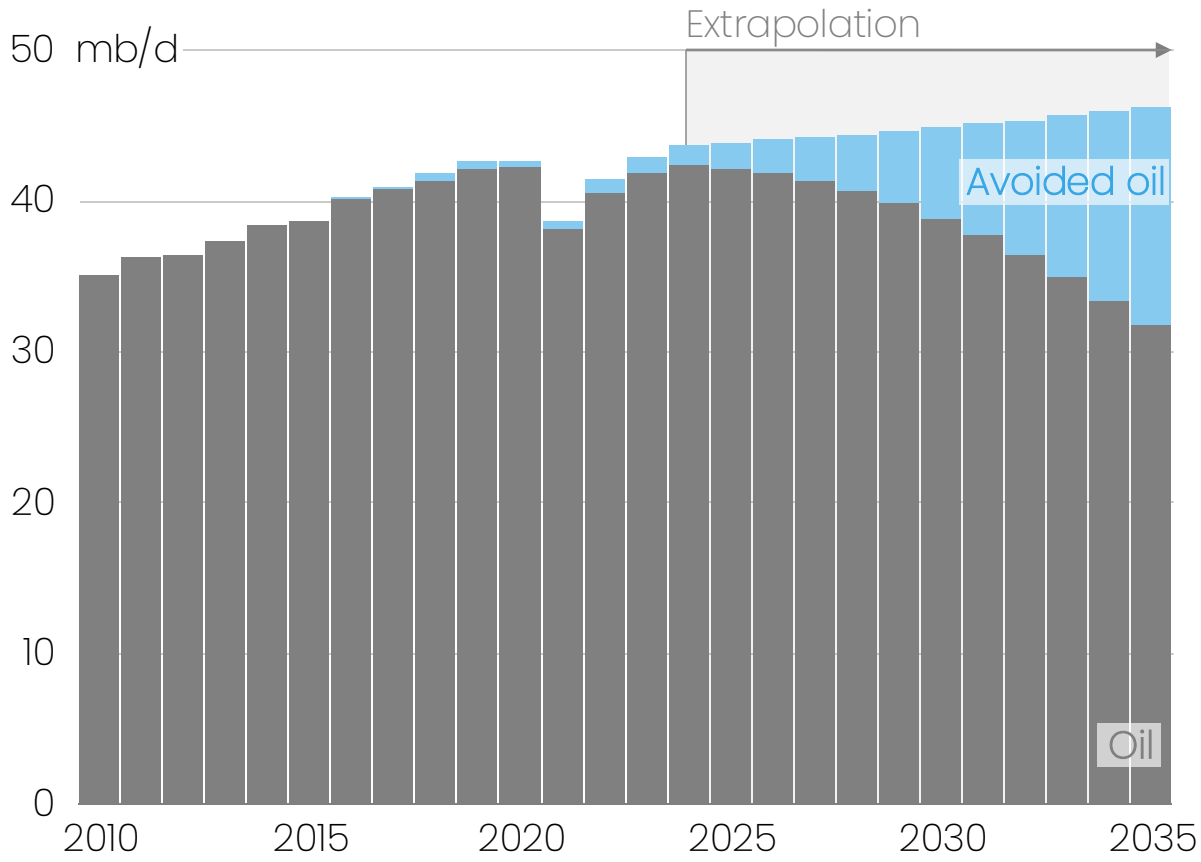
Road transport is the soft underbelly of the oil system

Sales translate into stocks within 15 years or less

Electric vehicle sales



Oil demand for road transport



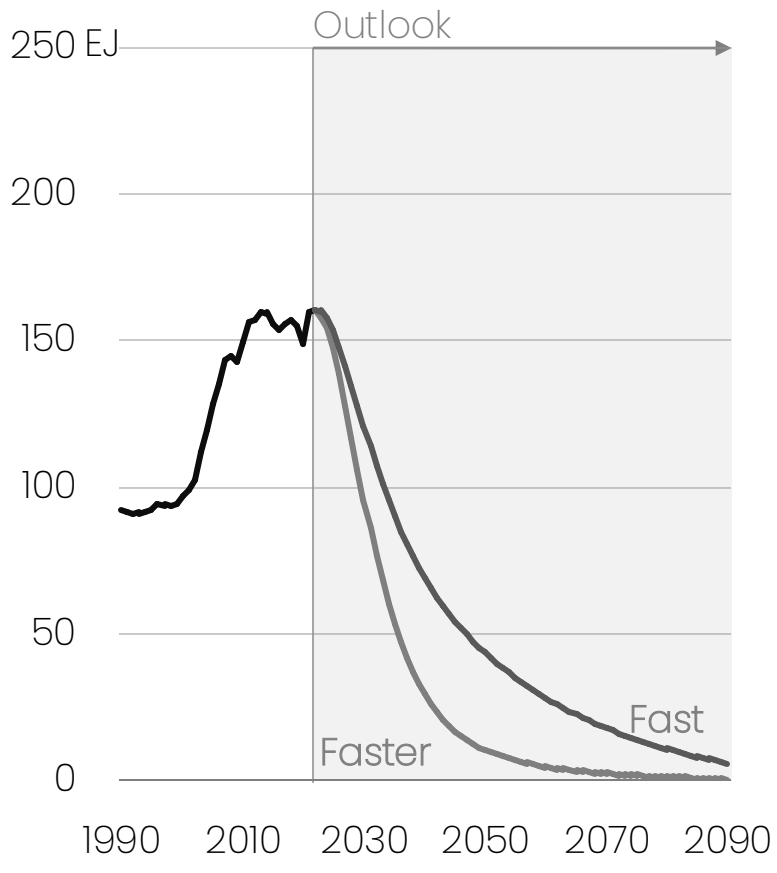
Sources: IEA (past), Ember Futures extrapolation. EV sales are modelled on logistic S-curves and converted to stocks using a standard scrappage formula.

EMBER

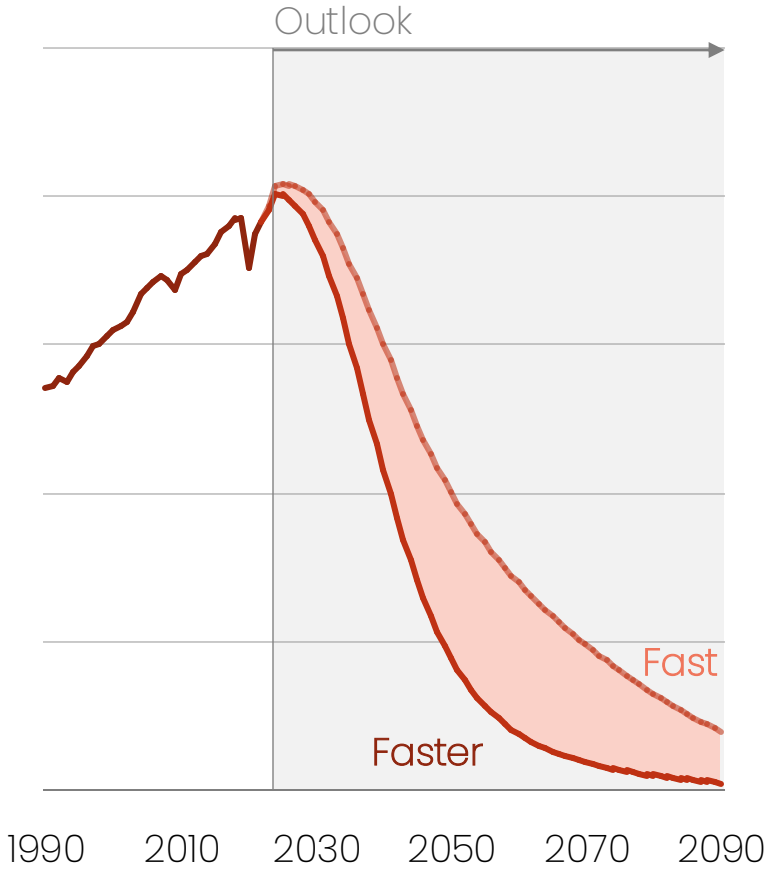
The growth of electrotech means the decline of fossil fuels

After taking all the growth by the end of this decade, electrotech will start to push fossils out

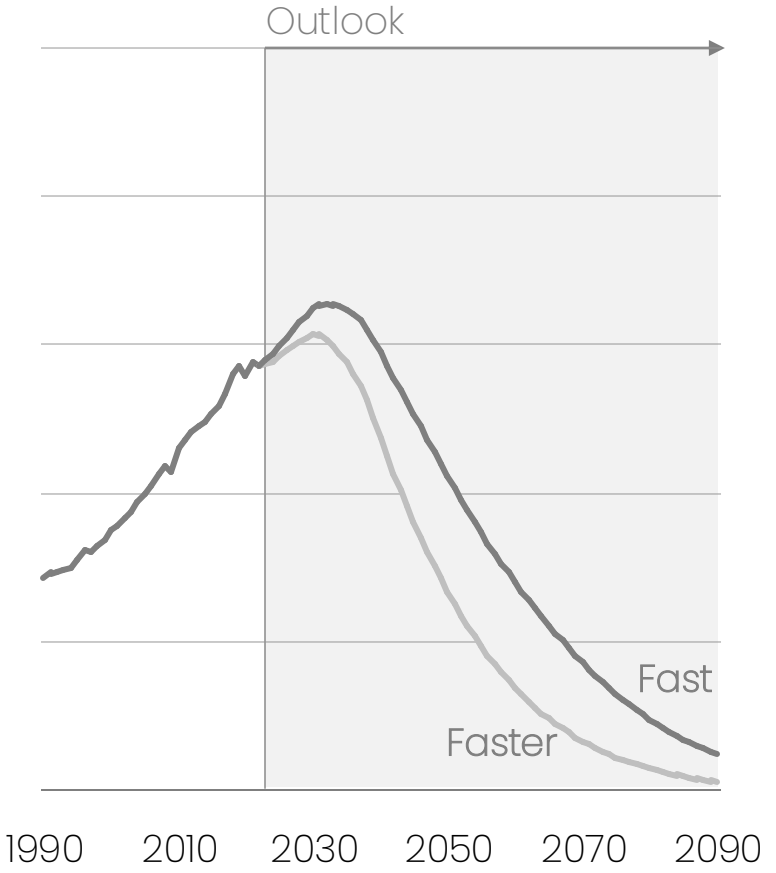
Global coal demand



Global oil demand



Global gas demand



Source: Rystad Energy (Fast 1.8°C, Faster 1.6 °C), RMI

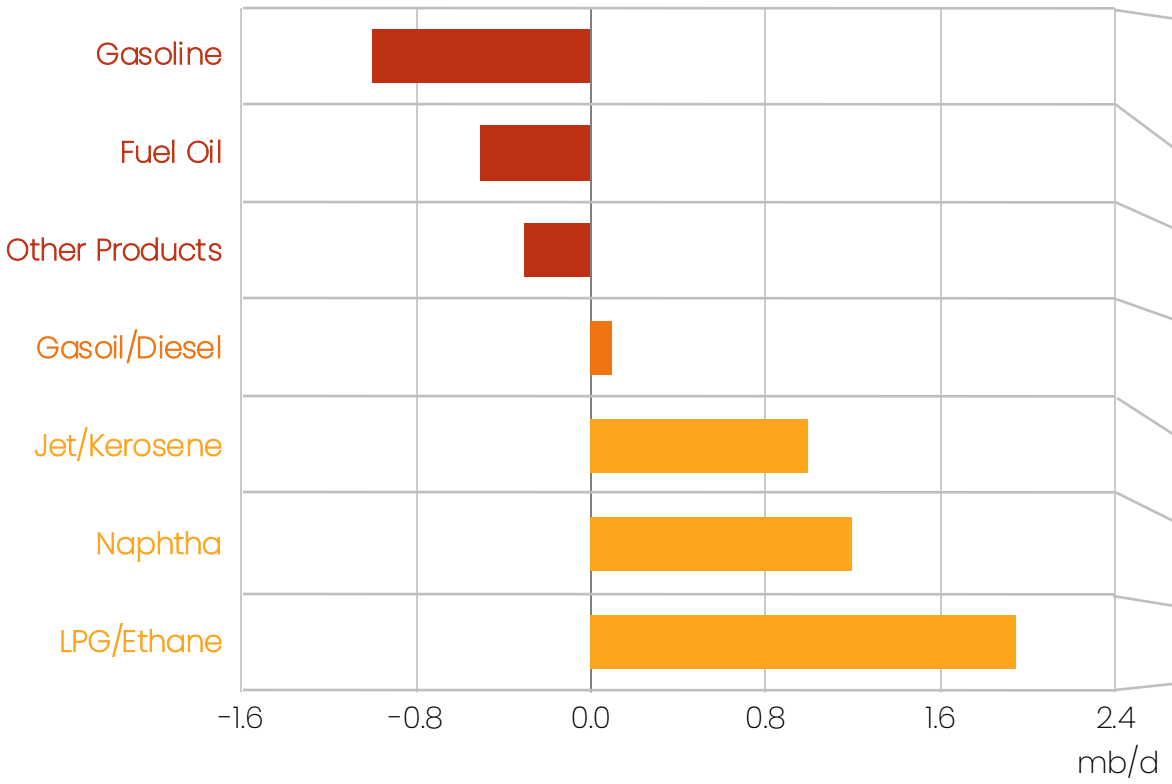
EMBER

Skewed oil demand will disrupt refining

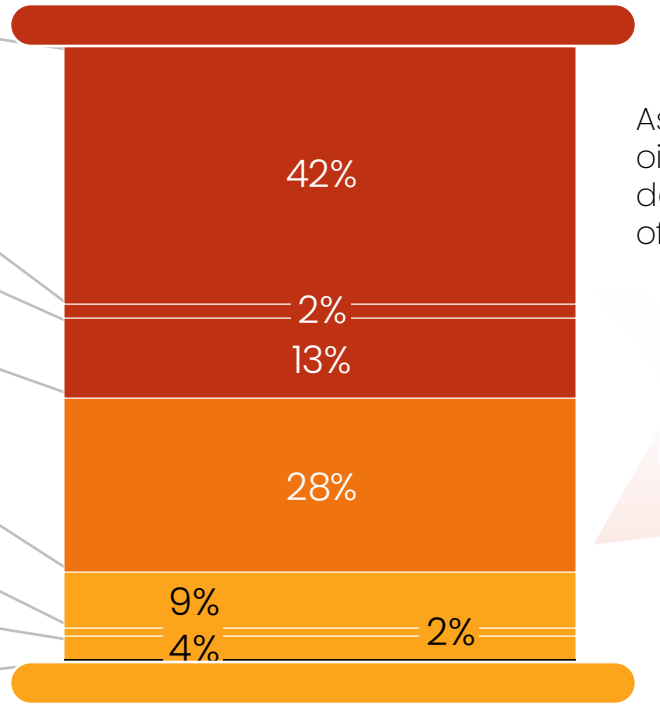
For the first time in history, the demand for a certain part of the barrel will start to structurally decline…

…which will put many refineries which are dependent on gasoline and other product revenues under pressure

Growth in world oil demand by product, 2024-2030



Typical yield of one barrel of oil in a refinery



As demand for gasoline, fuel oil and other products falls, it depresses prices for over half of typical refinery output

Only more complex refineries can shift (some) of the barrel to kerosene or other chemical products — many refineries cannot and will struggle

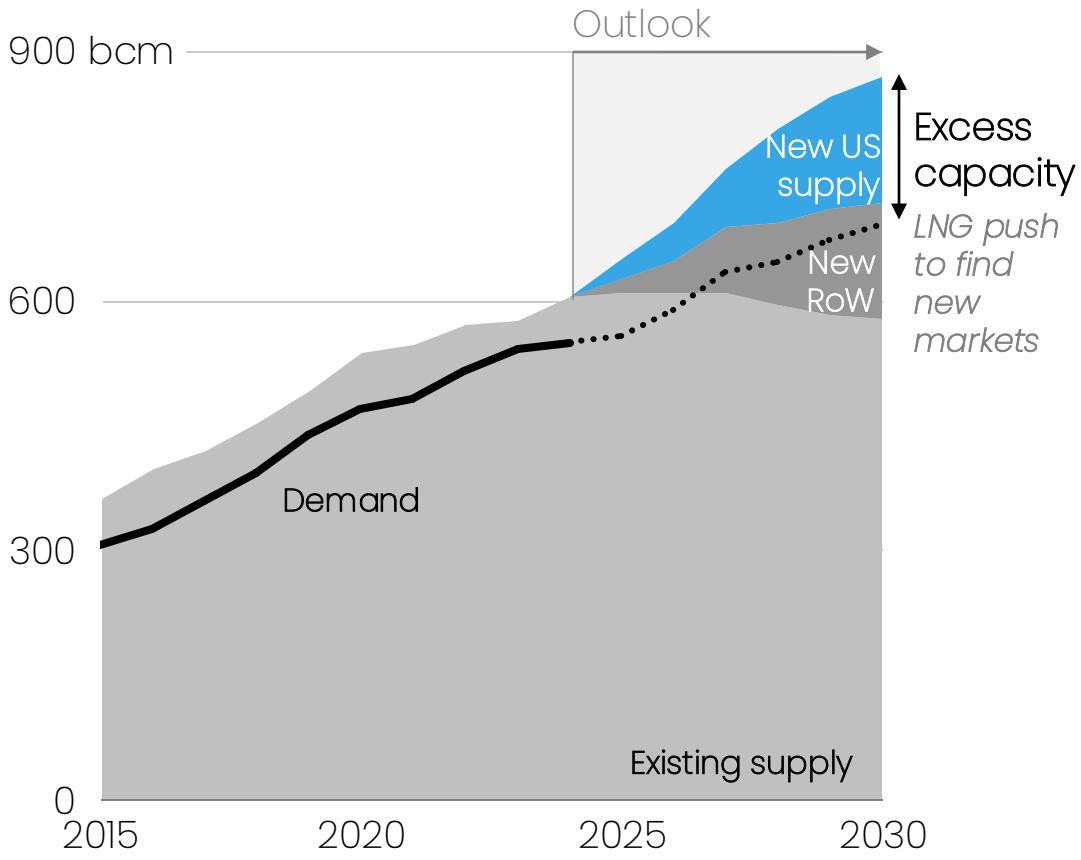
Sources: IEA; EIA; Ember analysis

EMBER

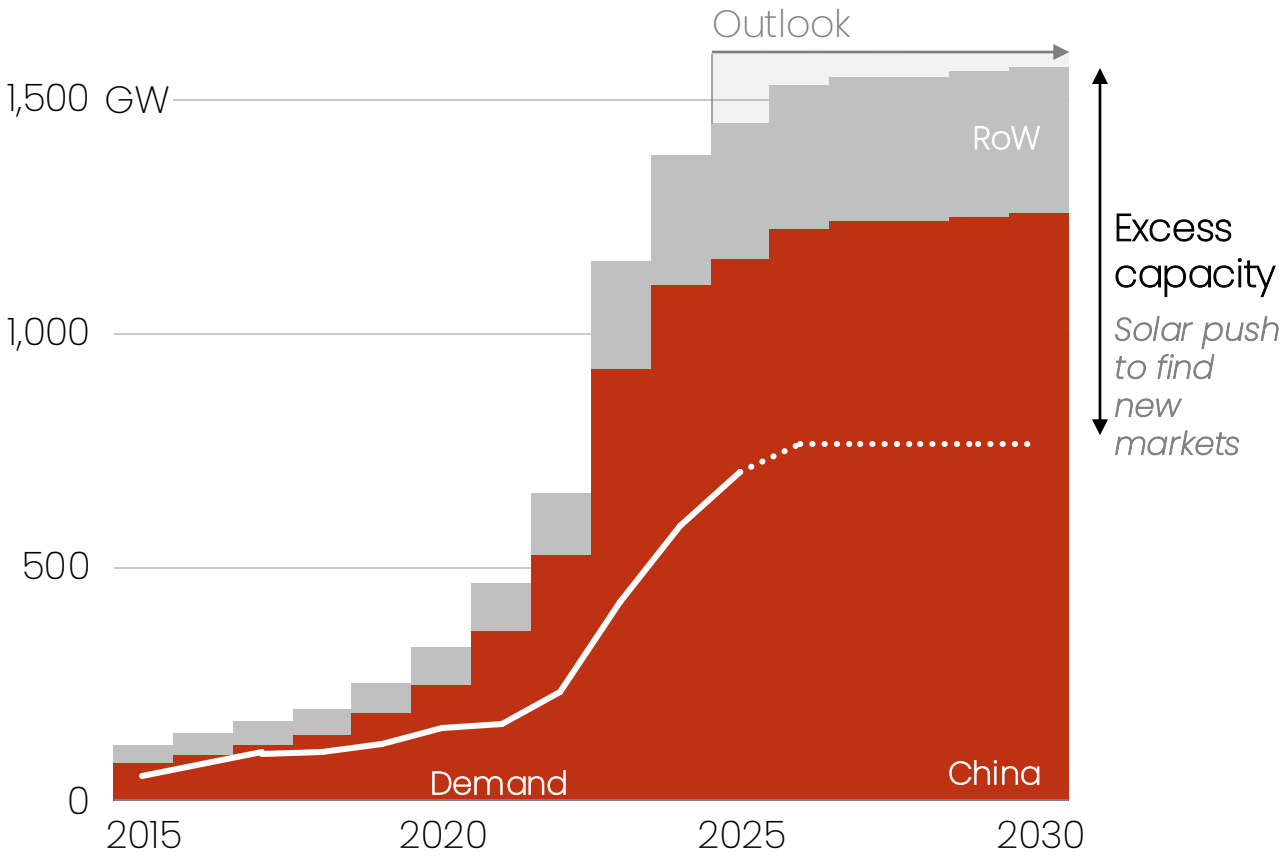
A battle between overcapacities

LNG versus solar is the great battle for the future of energy

LNG overcapacity – supply and demand



Solar PV module overcapacity — supply and demand

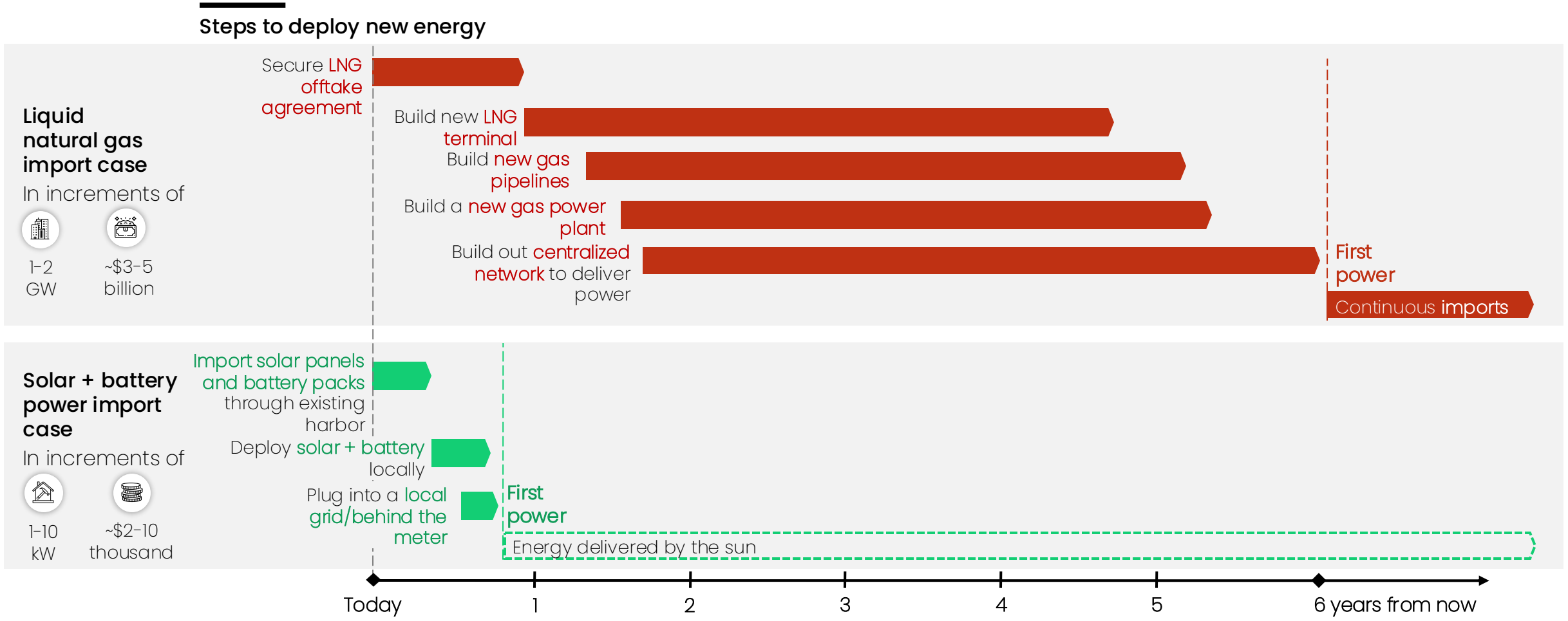


Sources: IEA; Ember analysis

EMBER

Solar will win the battle for the energy future

Because solar offers a better deal: more efficient, faster, cheaper, and local



Sources: Rystad, Ember analysis • Note: timelines are averages and indicative

EMBER

Chapter 5.2
Wider implications of changes in energy

01

Energy change means system change

IT and AI have brought the marginal cost of information down to the marginal cost of electricity. Electrotech is now doing the same for energy itself, pushing its marginal cost toward zero. Together, this unlocks a world of abundant energy and information. That means the end of oil intensive development.

02

Winners will be digital and solar-powered

A new class of industrial nations will rise—those with both abundant sunlight and the AI to harness it. The opportunity is greatest in the global sunbelt.

03

Losers will be those who cling to the old

As fossil demand slips off the plateau, price swings will intensify—triggering crises for countries and companies that remain dependent on fossil revenues for too long. Fossil assets at the top of the cost curve will be stranded, and returns to new fossil projects will disappoint.

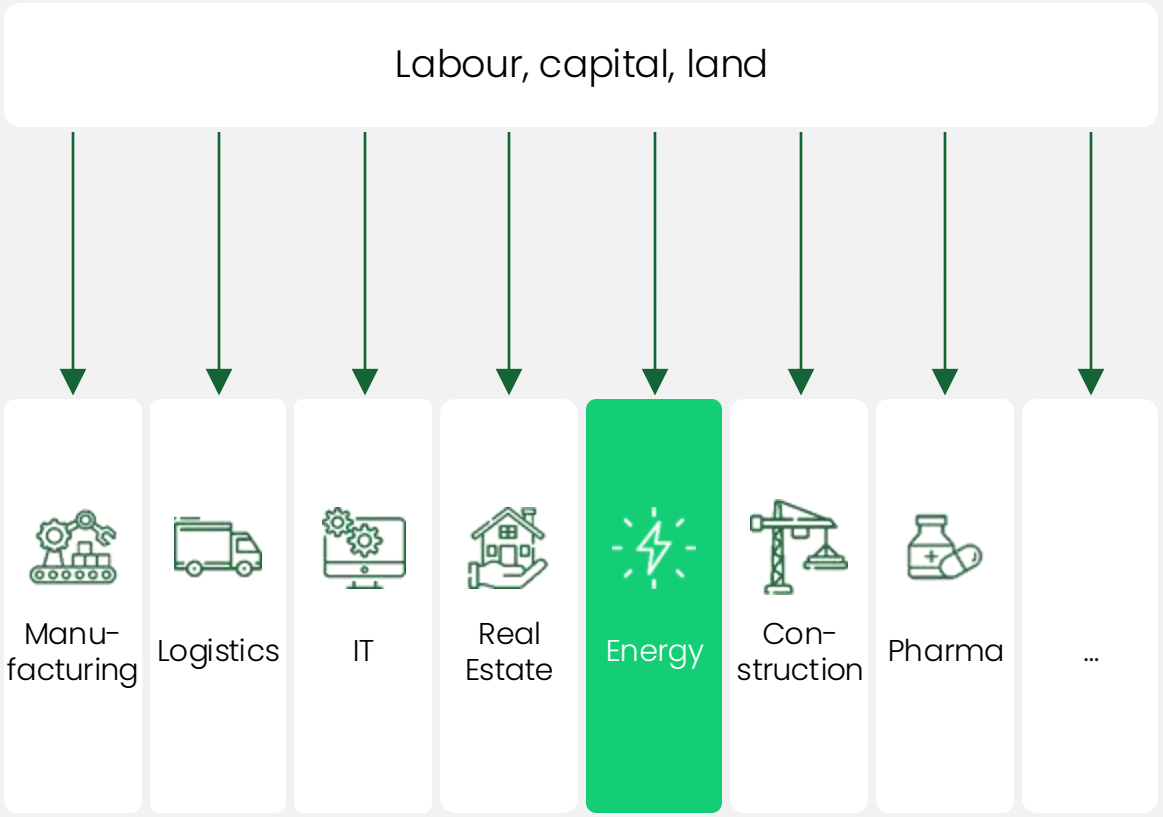
>> Return to Table of Contents

EMBER

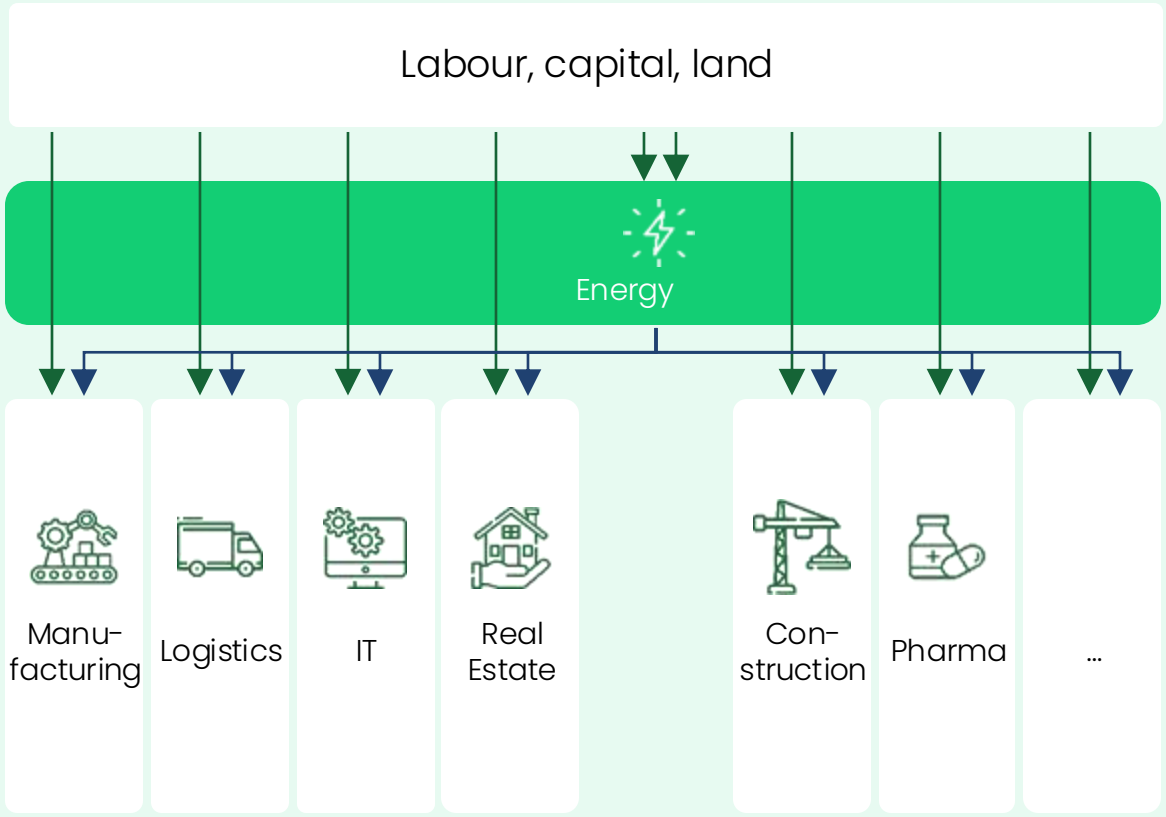
Everything is driven by energy

So energy transition means economic transition

The conventional, wrong view of the energy sector



The more accurate, systemic view of the energy sector



Sources: Ember

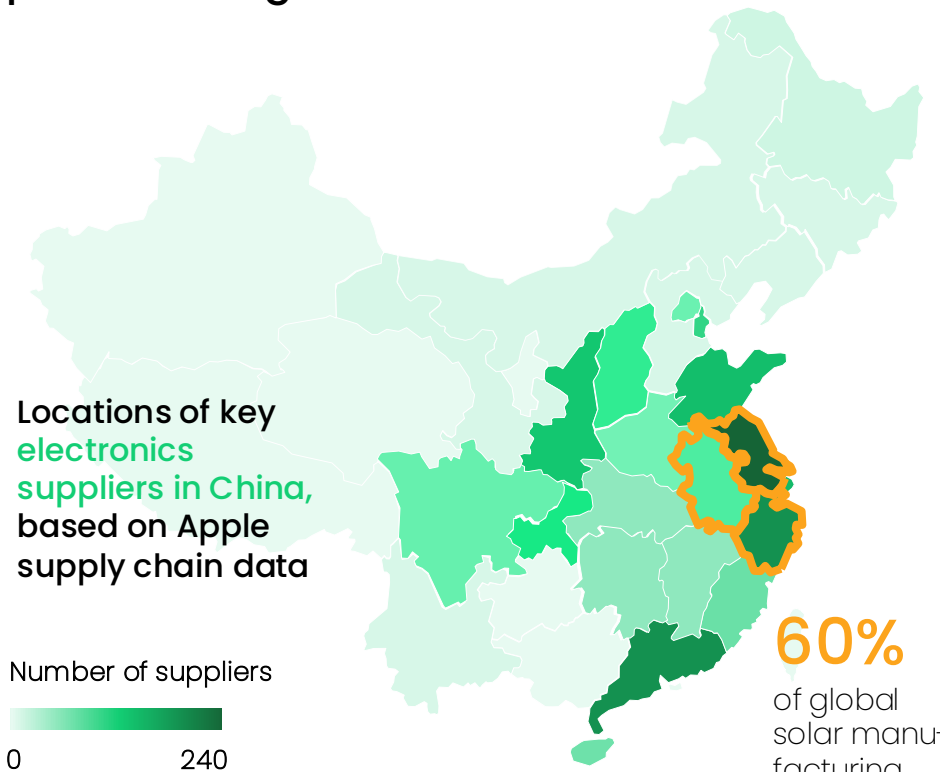
EMBER

Tech is coming for the energy sector

The same people and places that made digital tech, mainly in China, are now making electrotech

ILLUSTRATIVE AND NON-EXHAUSTIVE

Electrotech is manufactured in the same places as digital tech



60% of global solar manu-facturing capacity

Many electrotech leaders started in digital tech

CATL

Robin Zeng Yuqun

Founder & Chairman

Spent a decade at ATL developing Li-polymer batteries for iPhones and other smartphones

BYD

Wang Chuanfu

Founder, Chairman & CEO

As GM at BAK Battery Co., scaled Li-ion cells for Nokia & Motorola phones

SUNTECH

Shi Zhengrong

Founder & Chairman (until 2013)

Led thin-film PV R&D at UNSW, pioneering semiconductor-style solar cell fabrication before commercial scale-up.

NIO

William Li (Li Bin)

Co-founder & CEO

Built Bitauto app as an online auto-services platform, before starting Nio

LONGi

Li Zhenguo

Founder & President

Early role at Huashan Semiconductor Materials, processing wafers for PC & mobile chips, building semiconductor expertise.

XPENG

He Xiaopeng

Co-founder & Chairman

Co-founded UCWeb, developing China's leading mobile-browser, then applied that mobile-tech know-how to EVs.

NEBULA

Huang Shilin

Former Vice Chairman & Deputy GM, CATL

Spun off ATL's CE-battery arm into EV focus, leveraging his battery-tech background in consumer electronics.

Li Auto

Li Xiang

Founder, Chairman & CEO

Created Autohome as a data-driven car-sales & AI platform, blending digital-marketing and automotive retail.

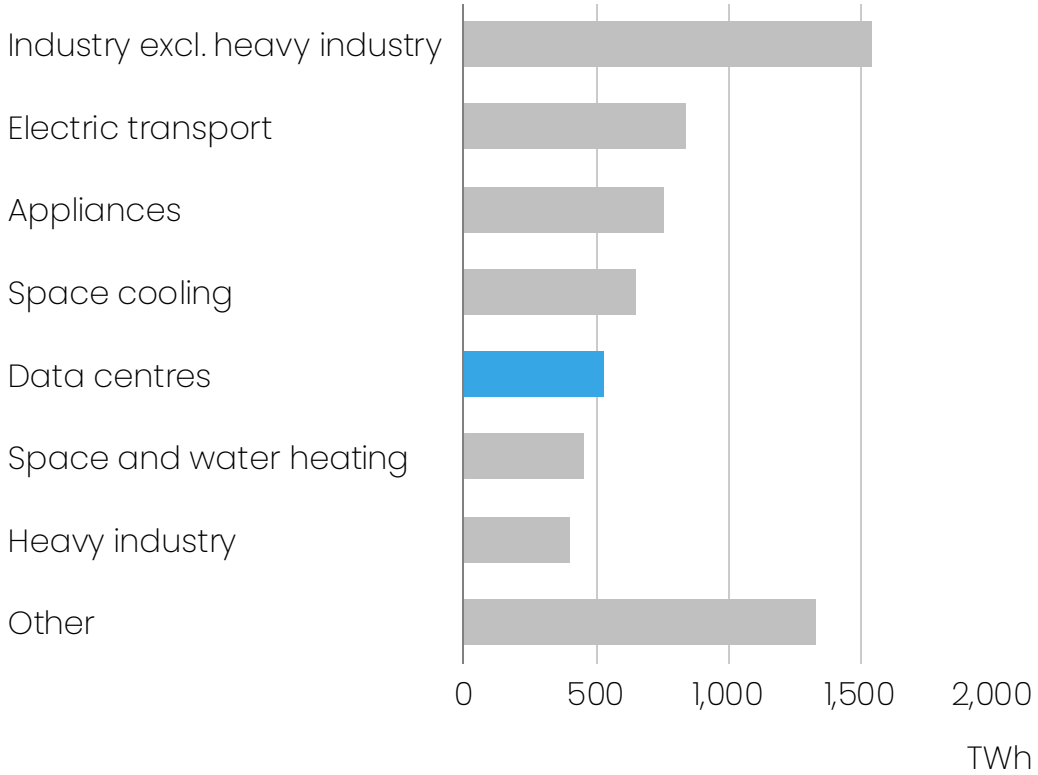
Sources: RMI; Bloomberg; FT; Apple; Ember analysis; Company websites; Press search

AI accelerates change

AI may raise electricity demand, but it is of tremendous benefit to scaling electrotech

AI energy demand growth in context

Increase in electricity demand by sector, 2024-2030



Impact of scaling AI on electrotech, examples

- Predictive maintenance
- Autonomous operations
- Smart charging
- Adaptive heating
- Grid optimisation
- Battery longevity
- Materials discovery
- Power-electronics tuning
- Automated permitting

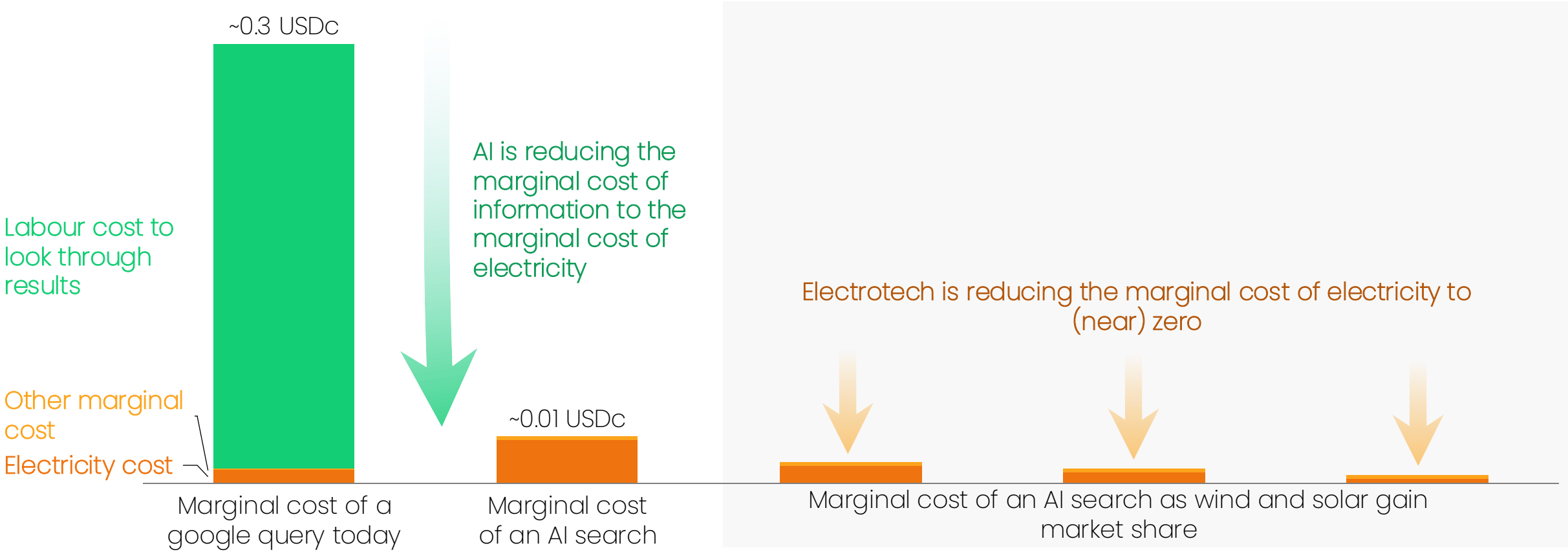
Sources: IEA Energy and AI; Ember analysis

The zero marginal cost economy is coming

Between AI and electrotech, the marginal cost of energy and information will fall dramatically

ILLUSTRATIVE

Cost of information



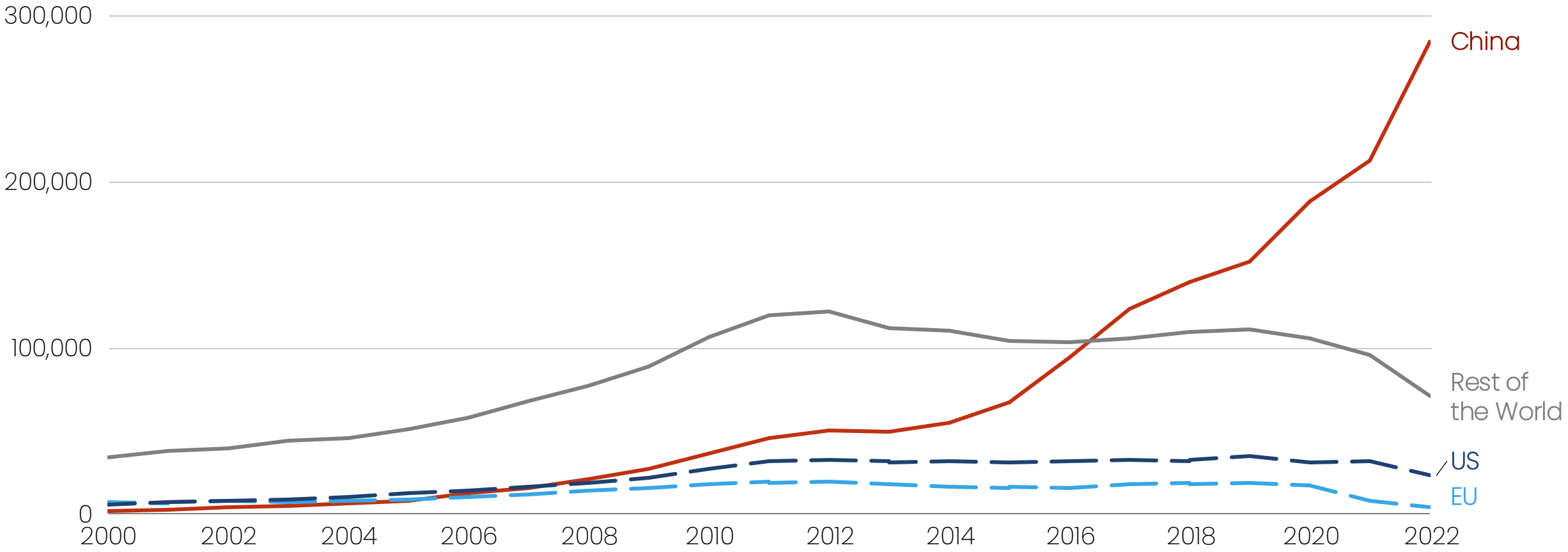
Sources: Google; Ember analysis • Note: this page focuses on marginal cost, not levelized cost; i.e., without capex write-offs

EMBER

The energy technology frontier has moved East

Patents are a leading indicator of where the leading companies of the future will be

Annual applications for patents in clean energy technologies



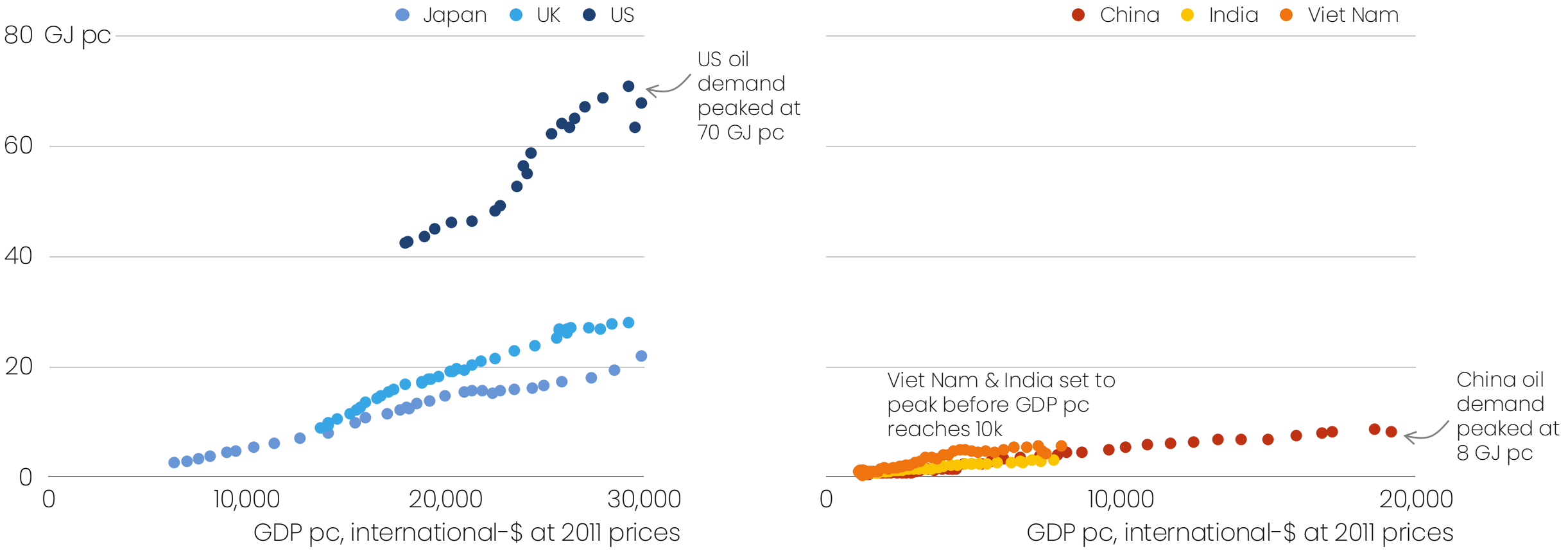
Sources: IRENA, Ember analysis

EMBER

The end of oil-intensive development

China's per capita road oil demand peaked at a tenth of US levels – other emerging markets are set to follow

Per capita road oil demand and GDP

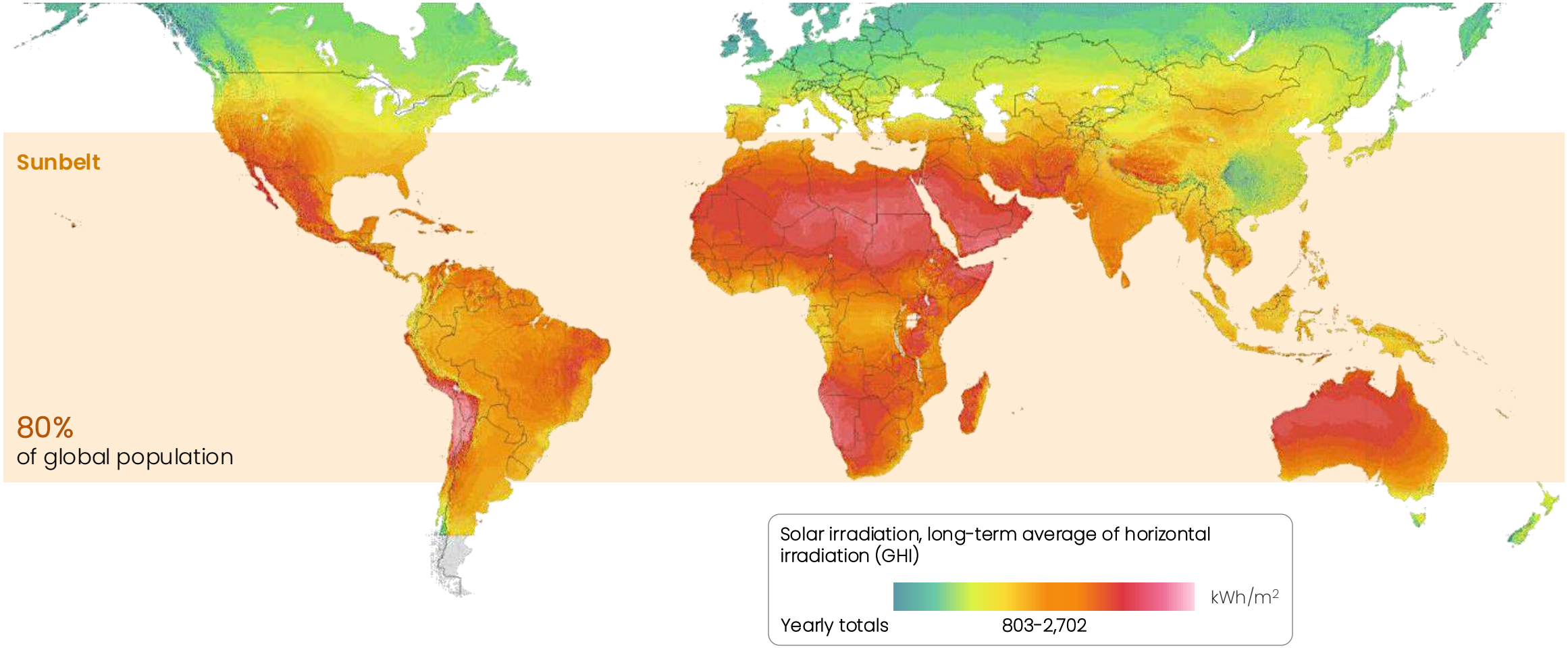


Sources: Maddison (via OWID), IEA WEB; Ember analysis. Note: LHS x-axis ends at 30k pc.

EMBER

Electrotech liberates the power of the Sunbelt

The emerging markets will have the lowest electricity cost



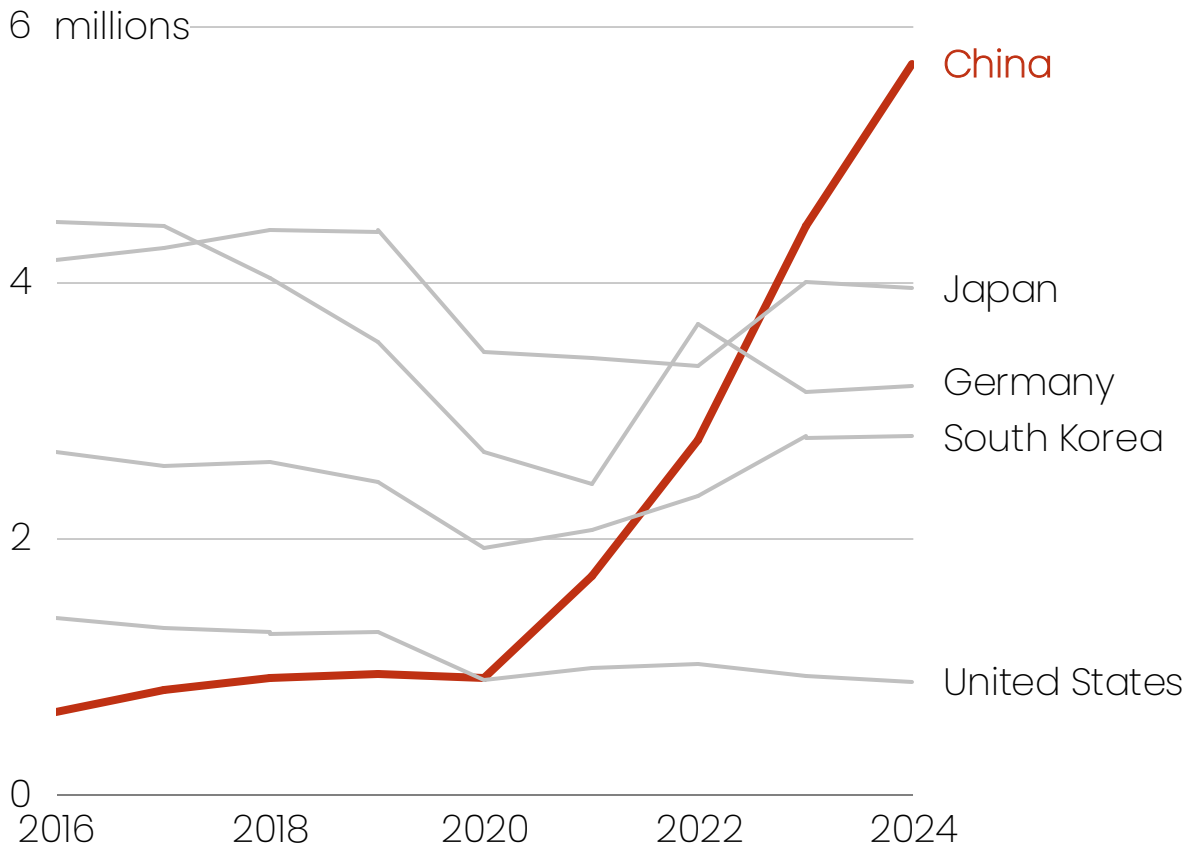
Sources: Global Solar Atlas, Ember. Map boundaries do not imply any judgment on legal status or sovereignty.
ETC for long-term forecasts of electricity costs by region

EMBER

The automotive sector is a warning sign for other industries

In four years, China went from small to dominant

Car exports: China is taking over, enabled by EVs



Role of automotive in selected economies

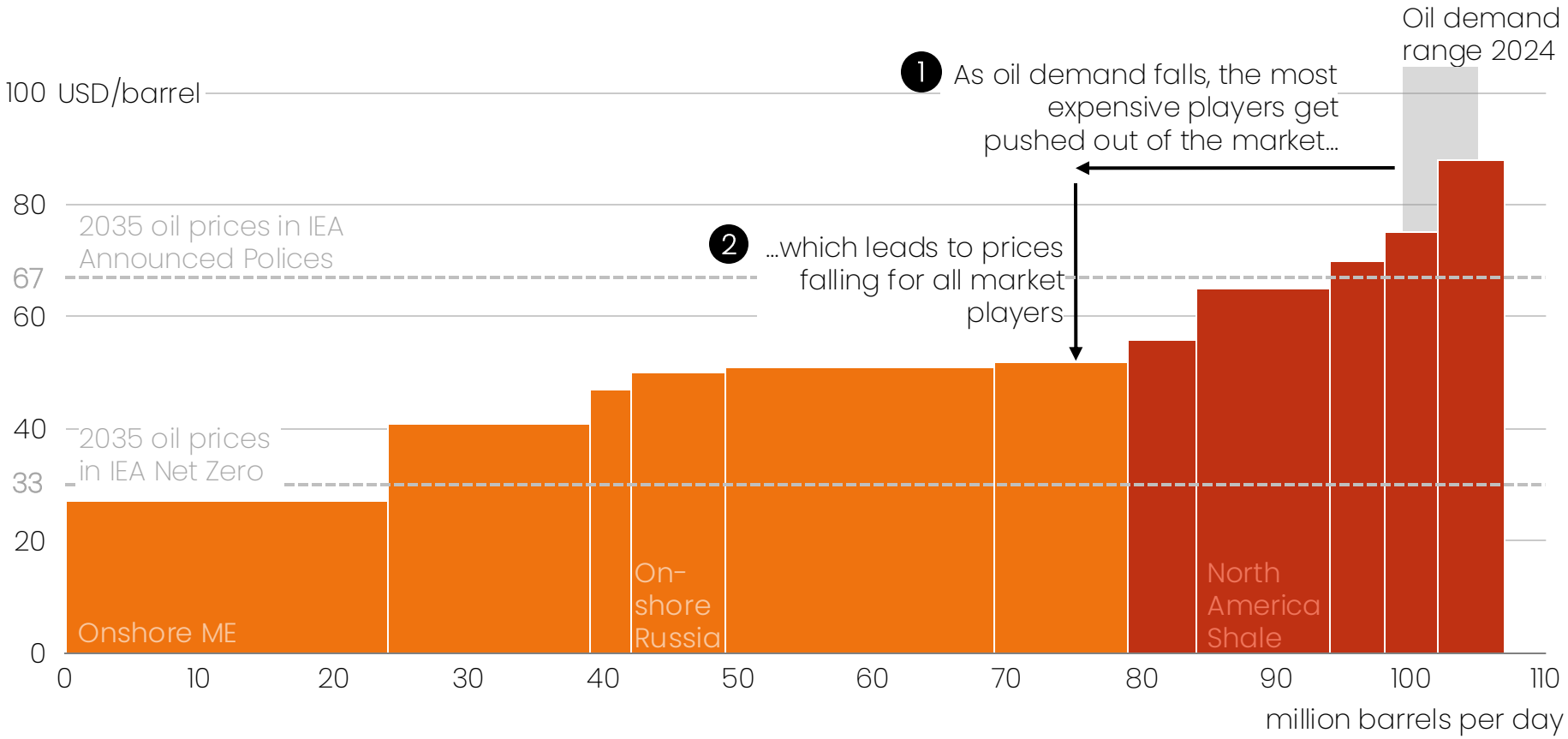
Sources: Alix Partners, NYT, OICA, Wikipedia • Note: 2024 values are estimated.

EMBER

The first few million barrels decline will hurt

Companies and countries dependent on the price of oil will face hardship as prices fall

Global oil supply cost curve



Notes

1. Top quartile is dominated by independents and majors, and fewer national oil companies. Even a few percent decline in oil demand can evaporate most of the production of some players.

2. Many petrostates need oil prices well over $50/bbl to have government finances break even:

Fiscal breakeven oil price

- Saudi Arabia: $98/barrel
- Iraq: $84/barrel
- Kuwait: $88/barrel
- UAE: $51/barrel

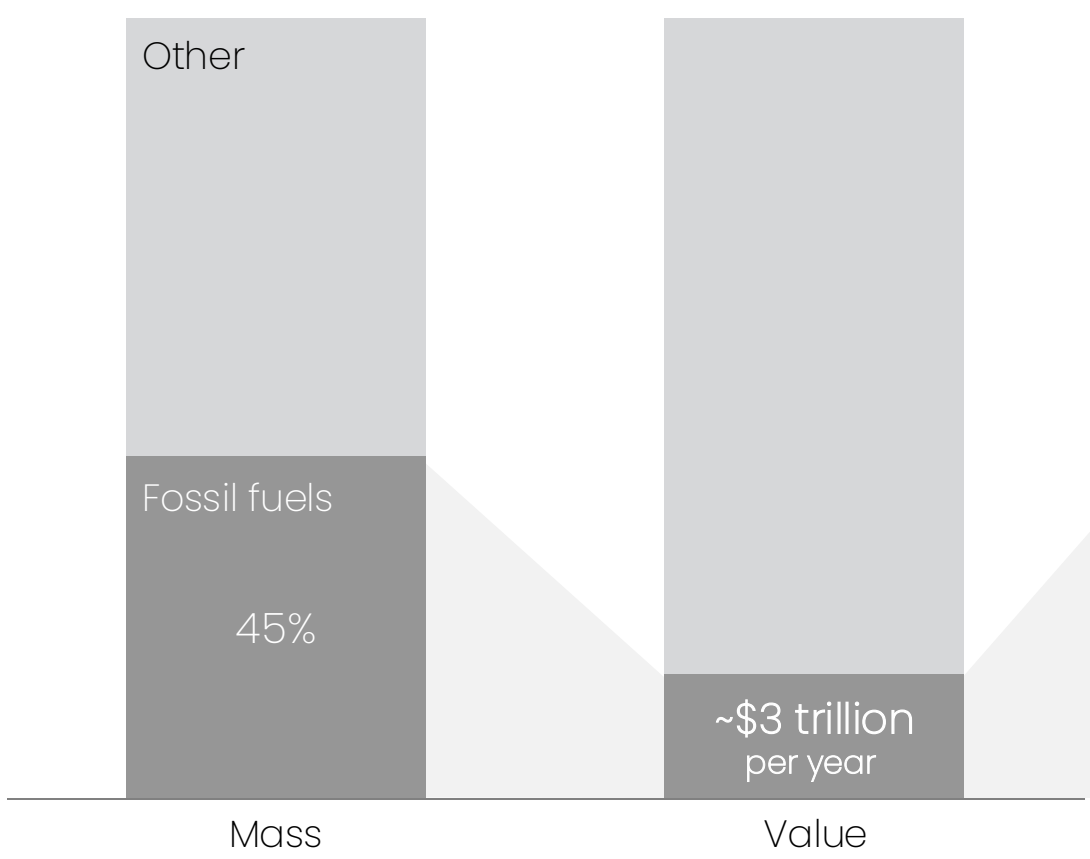
Sources: Rystad; IEA; Ember Analysis

EMBER

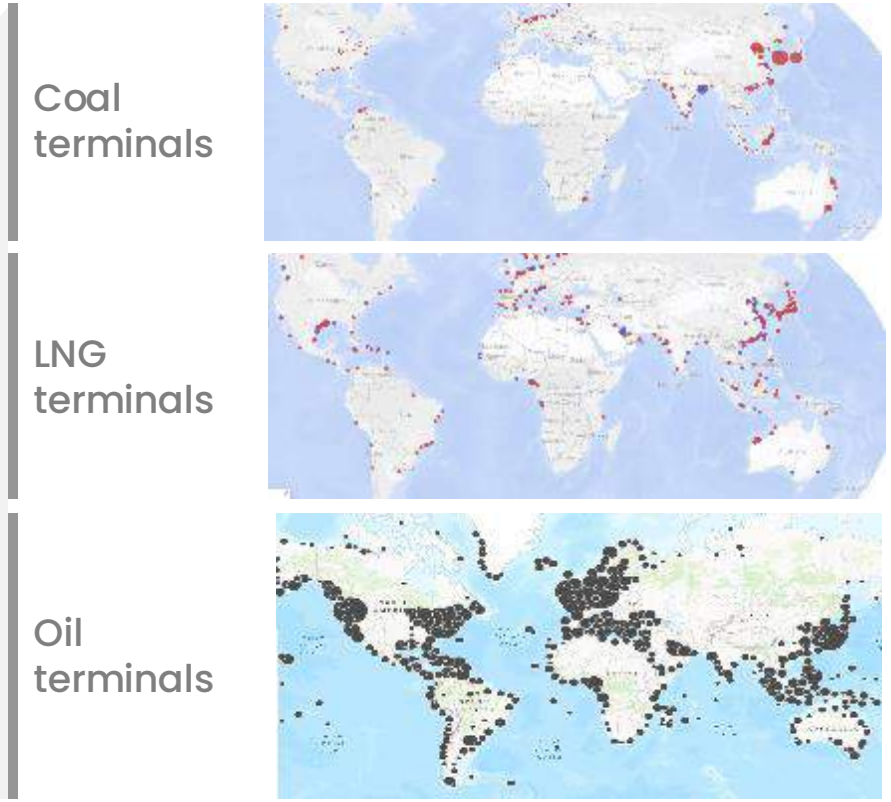
Fossil demand decline will have much wider implications

For example, ports all over the world are set to lose major customers

Share of global shipping from fossil fuels



Fossil ports around the world



Sources: Global Energy Monitor; IEA; Ember analysis

EMBER

Chapter 6
Seize the opportunity

01

The time is now

This is the decade that everything changes. Leaders will build the capacity, electrotech prices will become irresistible, electrotech will continue to grow up S-curves, and fossil demand will start to decline. It is time to rethink standard energy models because by 2030 the new reality will be priced into markets.

02

Change is hard

Inertia and the lobbying power of incumbents combine to make change difficult. It is hard to deploy new technologies and identify future leaders. Even policymakers who want to drive change can pick the wrong solutions.

03

Intelligent policy action is vital

Policymakers who wish for their countries to reap the benefits of the electrotech era need to rethink their strategy. That means getting the price of electricity down and electrifying end demand. It also means experimenting with policy, and moving on from failed solutions.

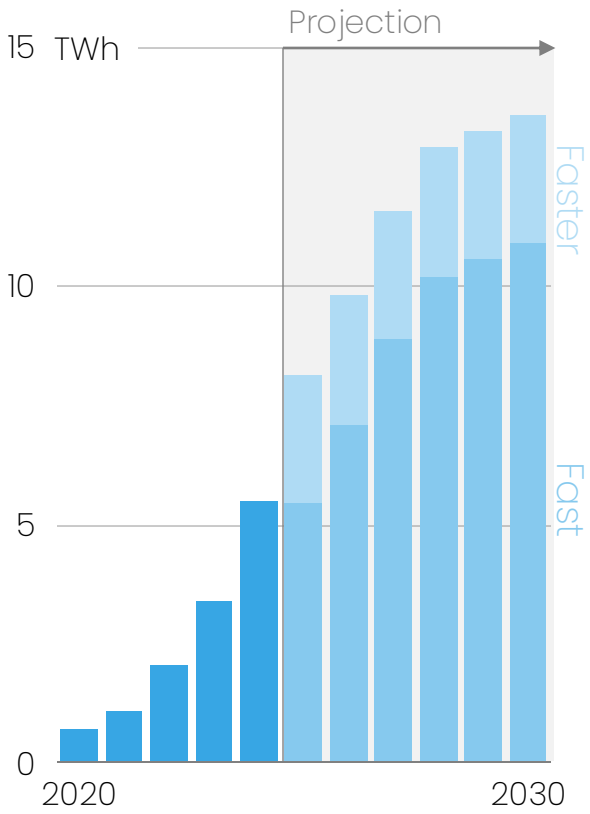
>> Return to Table of Contents

EMBER

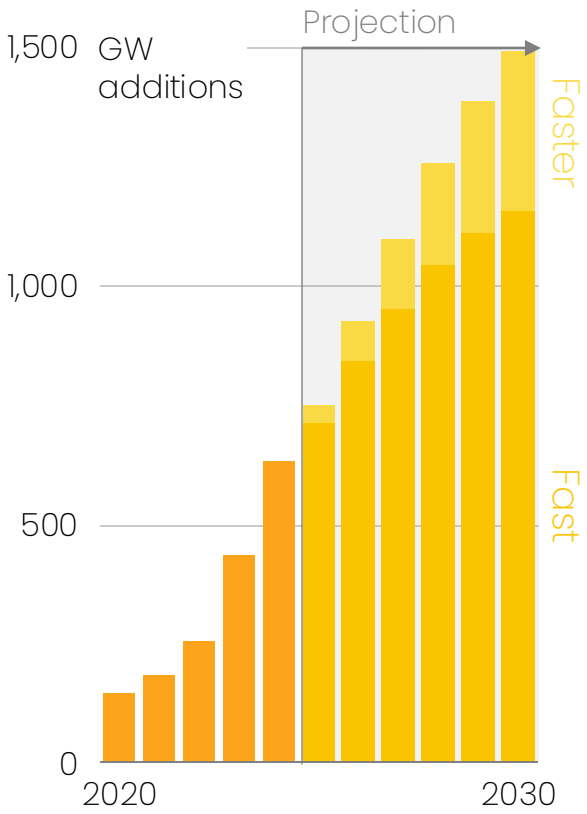
This is the decisive decade

A century in the making, electrotech will define this decade

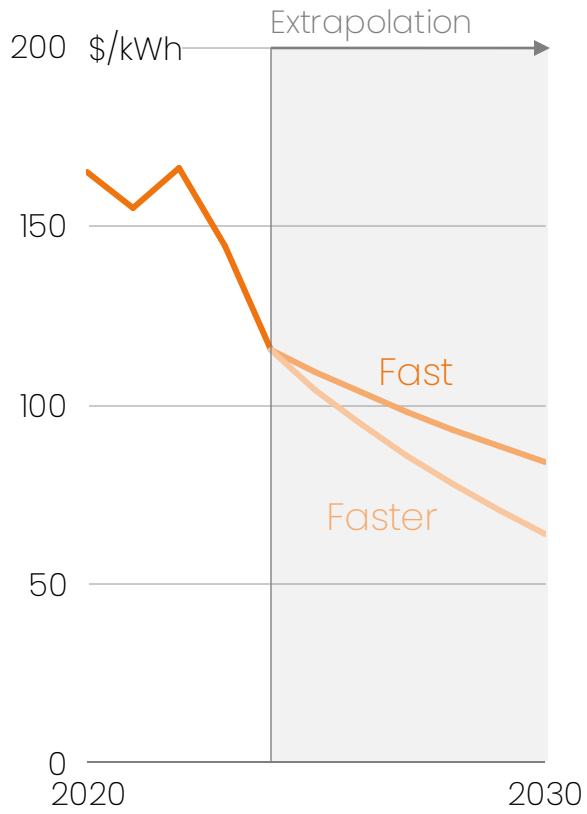
Manufacturing capacity is built: Batteries



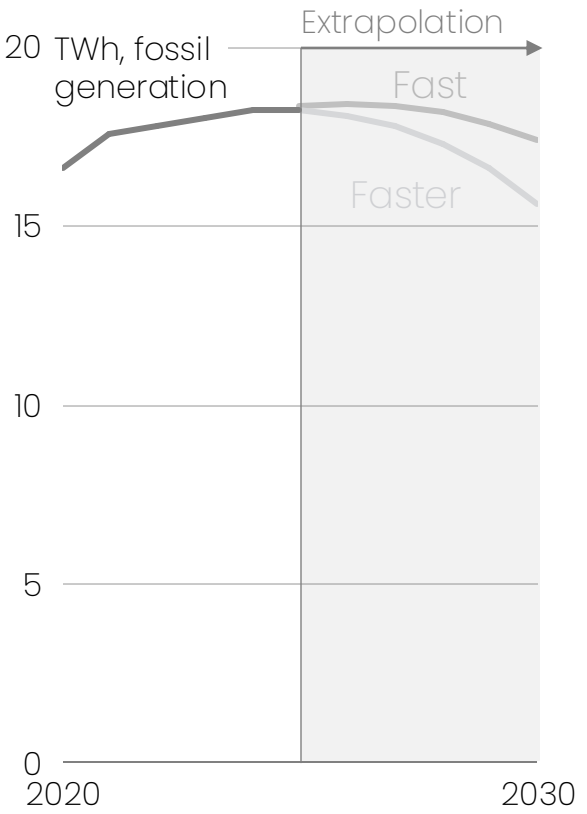
S-curves hit their steepest parts: Solar



Electrotech get too cheap to resist: Batteries



Fossil fuel demand enters terminal decline



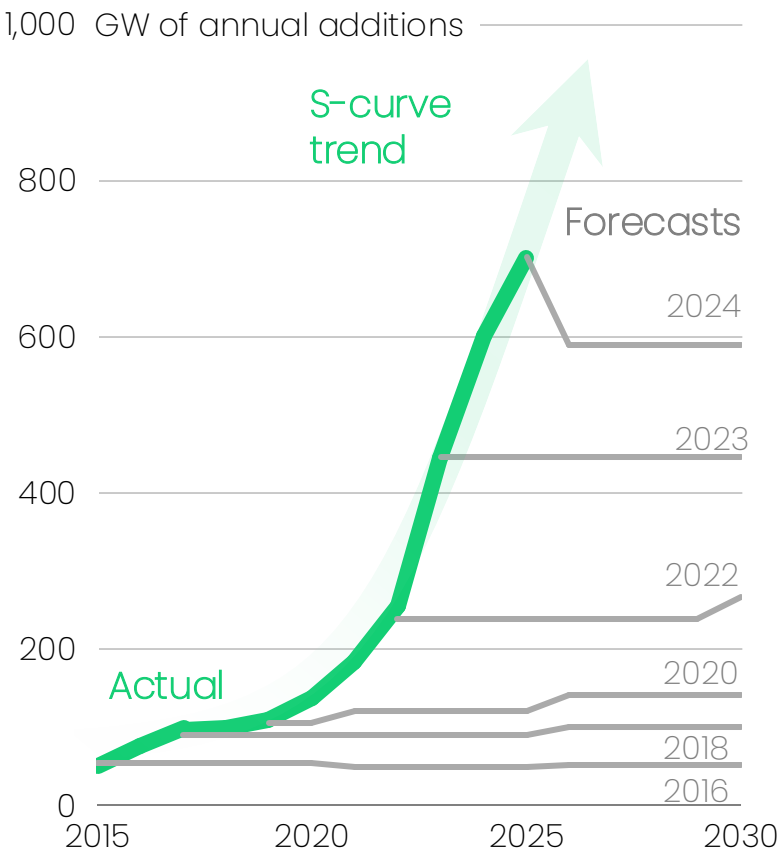
Sources: BNEF, RMI, Ember Futures extrapolation for fossil fuel demand, assuming 3% growth in electricity demand and 15-20% growth in solar and wind supply

EMBER

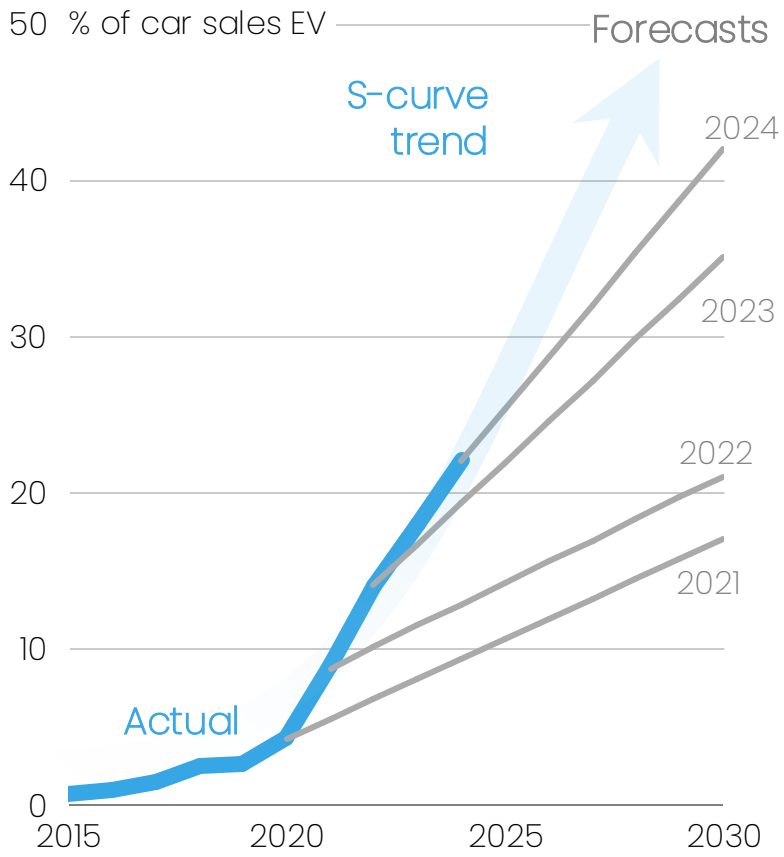
Beware of the limits of old energy models

Complex models are missing the reality of exponential change

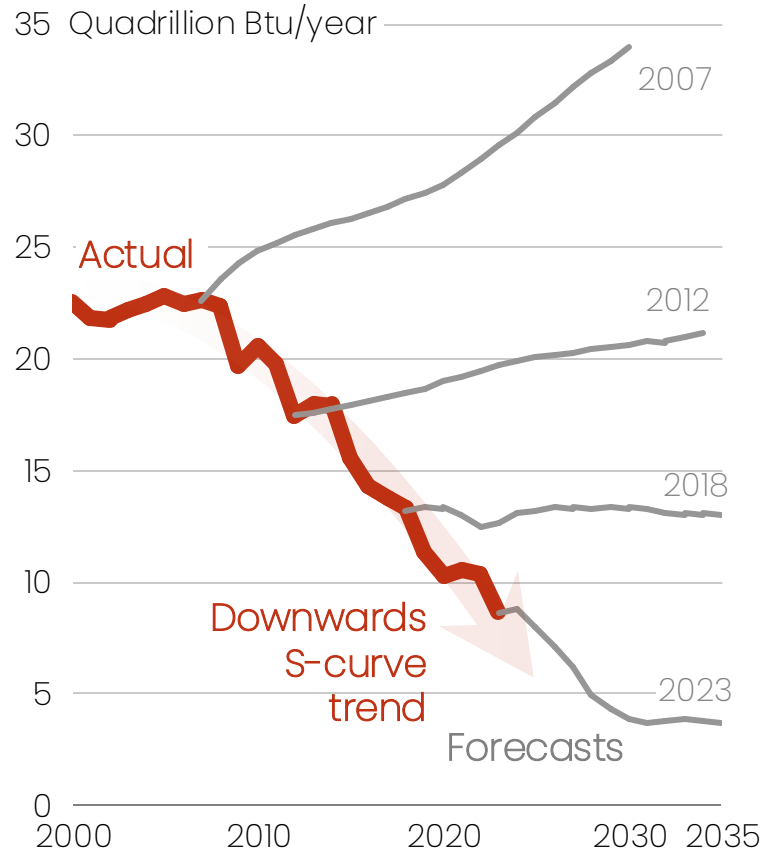
New solar additions



EV share of sales



US coal demand

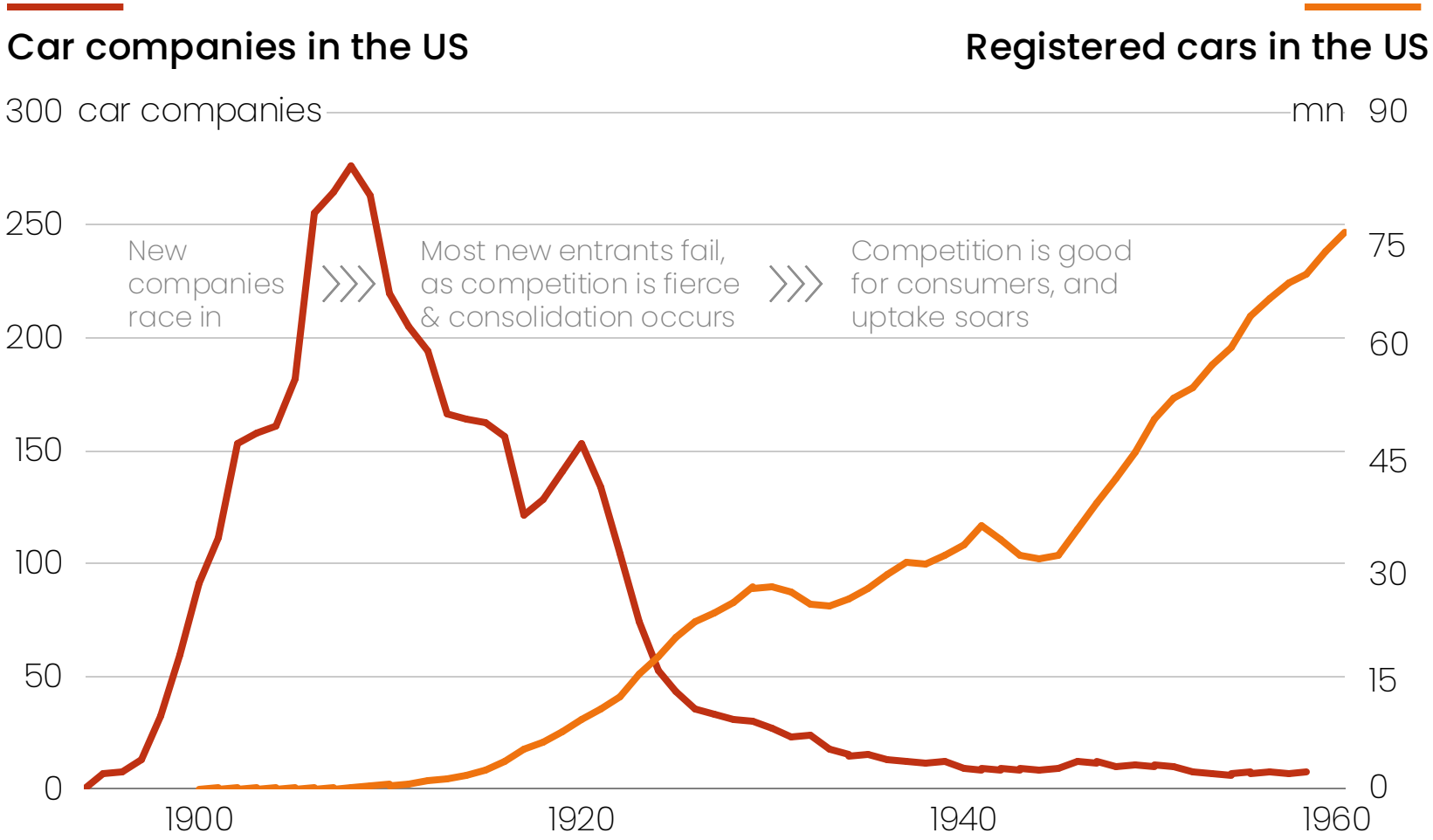


Sources: BNEF (solar actuals), IEA STEPS for WEO forecasts (solar & EVs), EIA via RethinkX (coal demand)

EMBER

Nobody said it was easy

Investing in technology revolutions is always risky



Normal playbook

01 Brutal competition drives overcapacity and shakeouts

02 Most new entrants fail in the early stages

03 Companies and investors chase growth before profits

04 Market volatility is highest during the early phase

05 The winners win big

06 Failure at the firm level is a necessary part of advance-ment at an economy level

Source: US Department of Transport, Mazzucato & Semmer (1999)

EMBER

Focus on the fundamentals

Three key questions to gauge new energy technology in times of peak confusion

Physics

Does it make the energy system **more efficient?**

Economics

Is it **small and modular**, so it can be manufactured at scale and **benefit from learning curves**?

Geopolitics

Does it **enhance the independence and security** of its user?

EMBER

Pick technologies that have the wind in their back

Many popular solutions will struggle in the face of reality

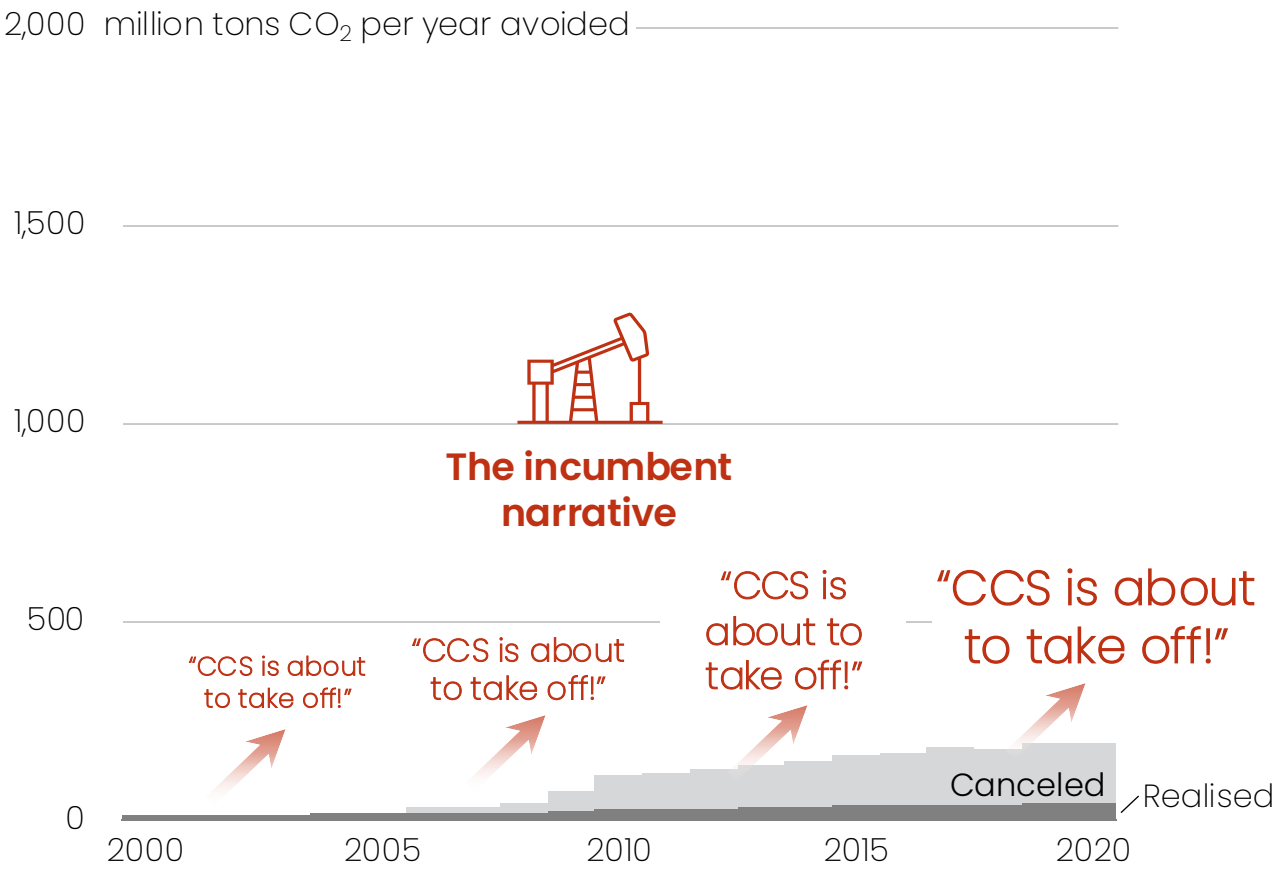
	Physics Does it make the energy system more efficient?	**Economics** Is it small and modular, so it can be manufactured at scale and benefit from learning curves?	**Geopolitics** Does it enhance the independence and security of its user?
CCS	✗ **No**	✗ **No**	✗ **No**
Biofuels	✗ **No**	✗ **No**	✗ **No** **unless you are Brazil**
Green hydrogen	✗ **No**	✗ **Not really** **except for the electrolyser**	✓ **Yes** **unless imported**
Electrotech	✓ **Yes**	✓ **Yes**	✓ **Yes**

EMBER

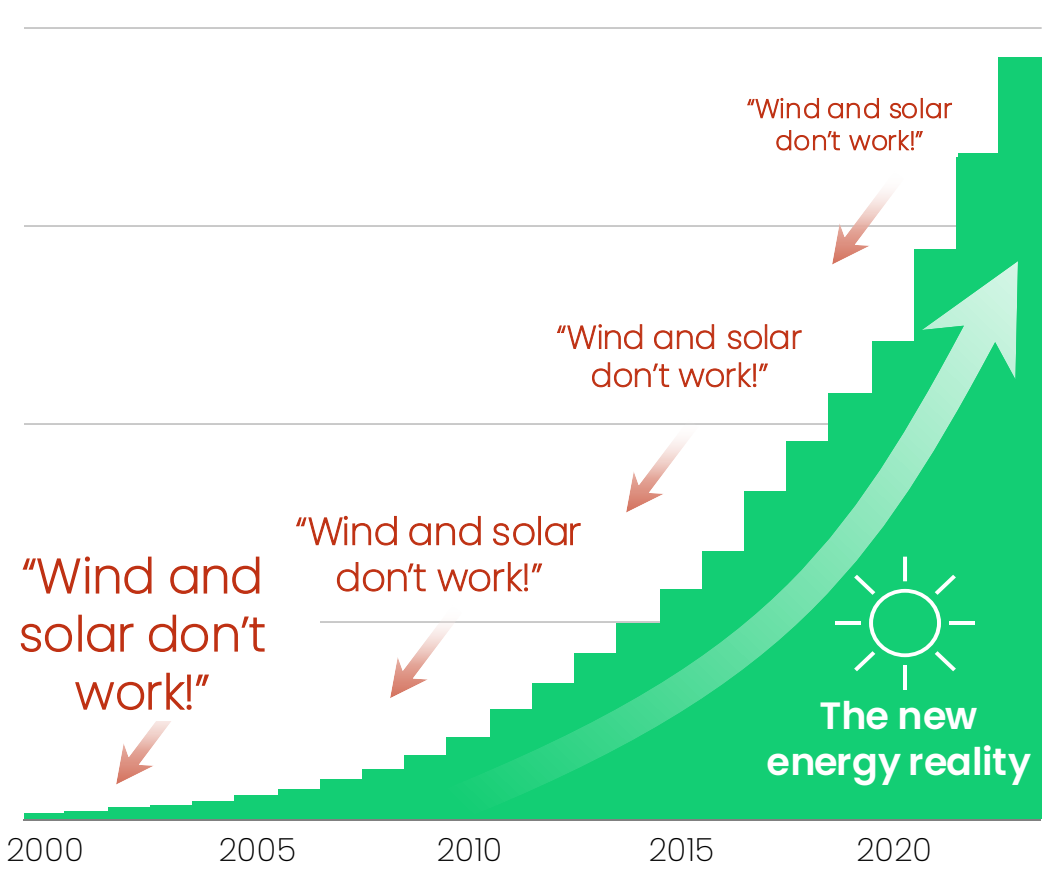
Avoid the distractions

Some cleantech only gets louder; electrotech actually delivers

Global installed CCS capacity



Wind and solar avoided emissions



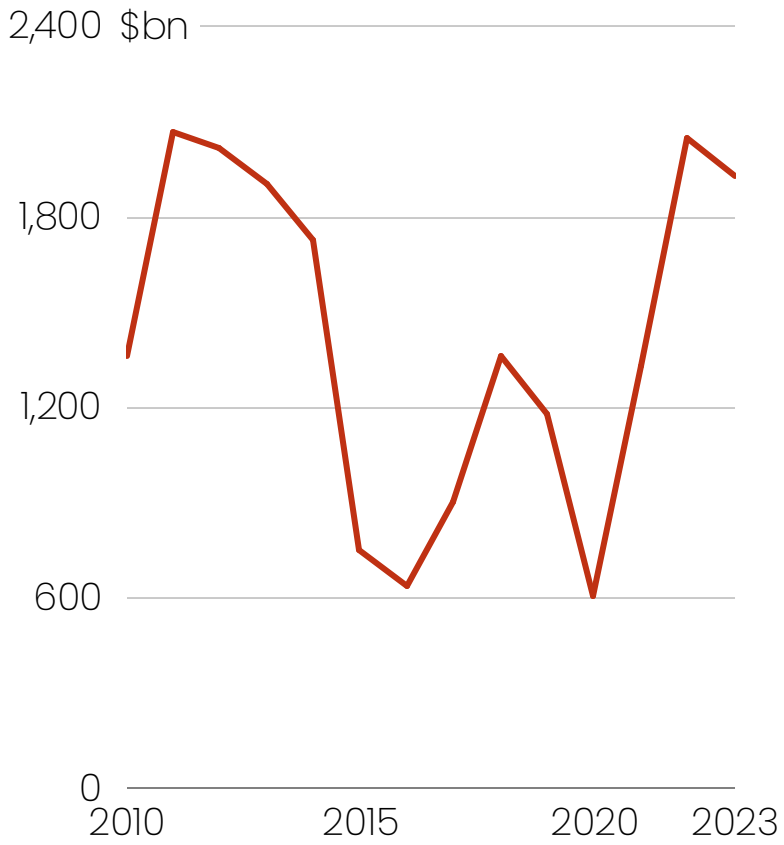
Sources: IEA, BNEF • Note: avoided emissions estimated based on average global grid emission intensity.

EMBER

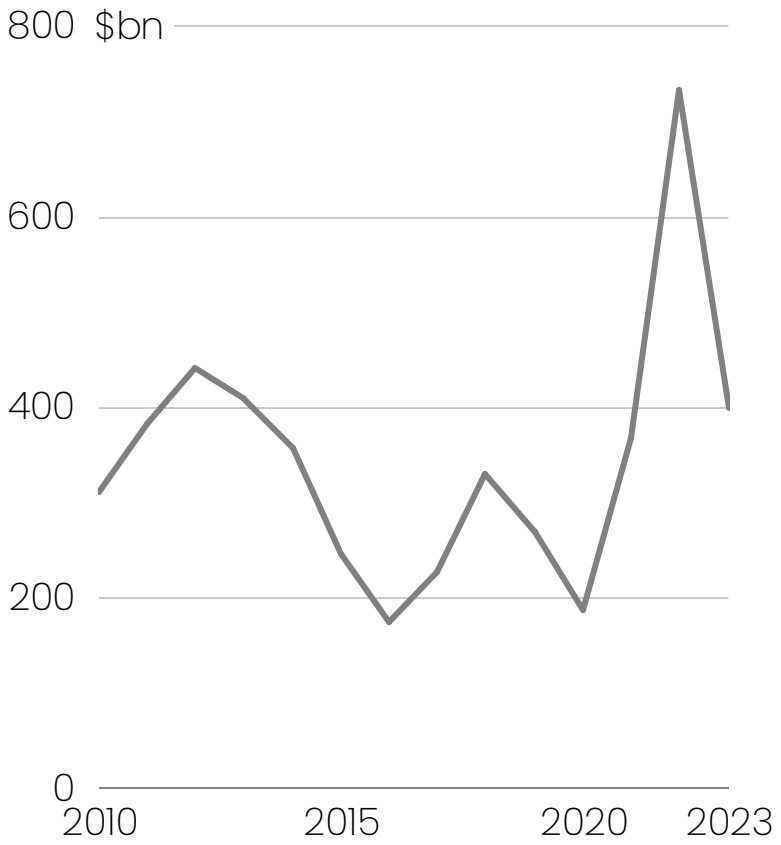
Incumbents resist change because the status quo is so profitable

Governments need to decide what is in their country's best long-term interest

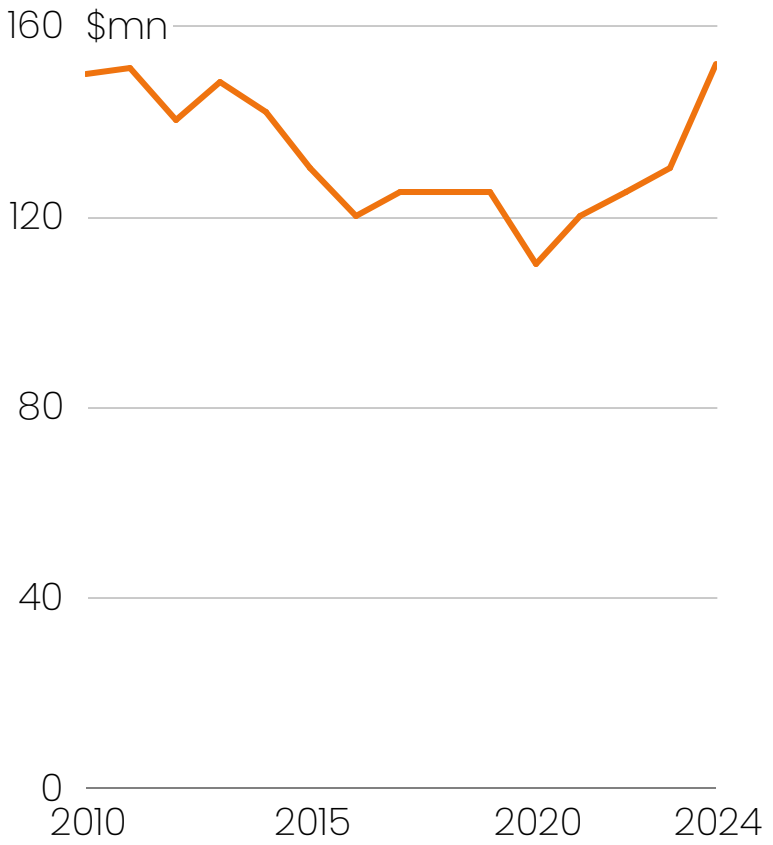
Oil rents



Fossil fuel subsidies



Oil and gas lobbying in the US



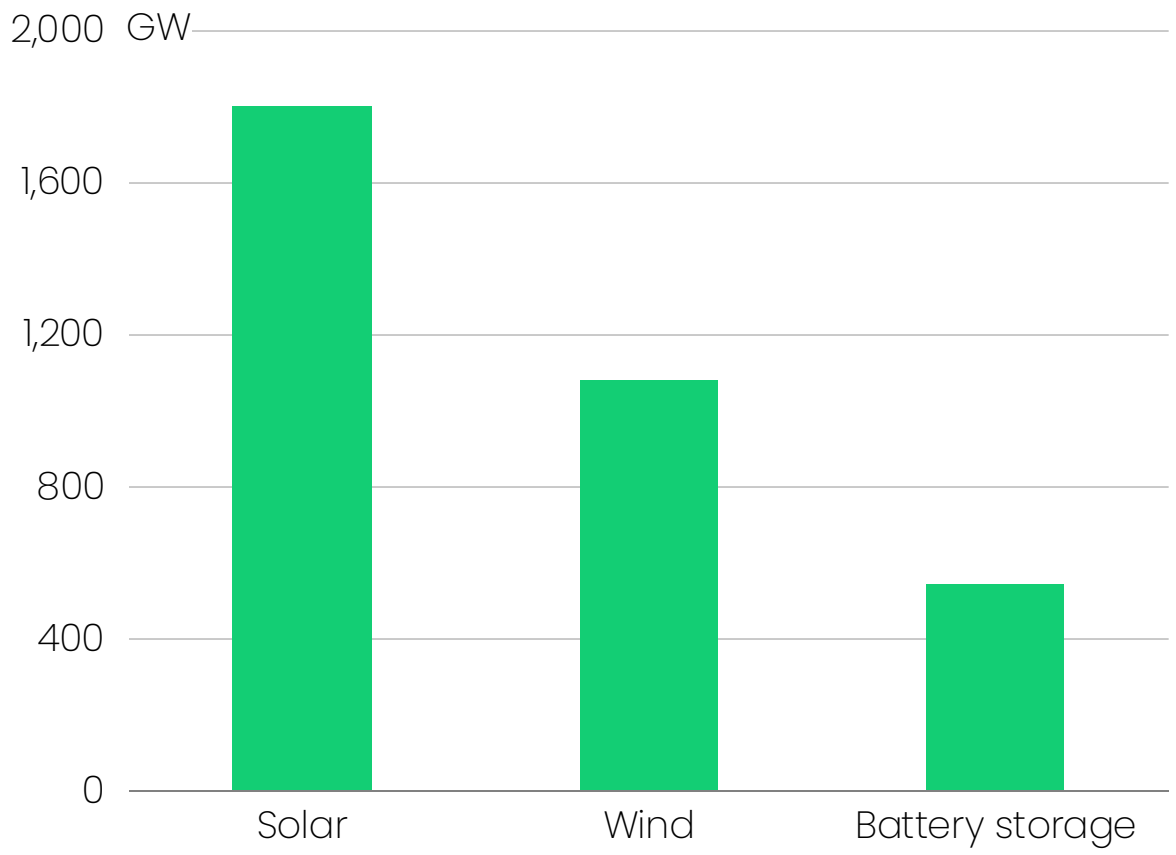
Sources: World Bank, IEA, Open Secrets

EMBER

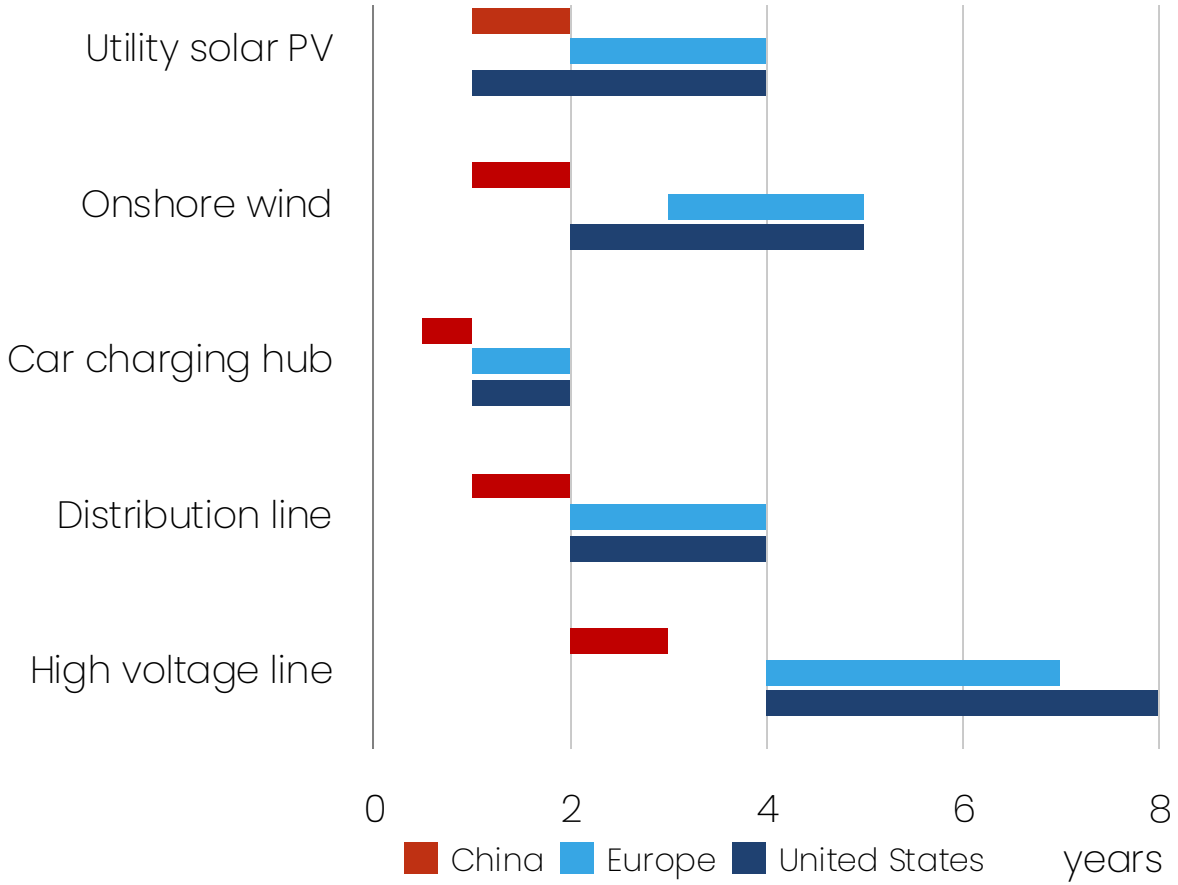
Back the builders not the blockers

Unlock the queues of electrotech that want to come online

Clean energy stuck in the connect queue



Typical deployment time



Sources: IEA. Note: solar & wind queue is global; battery storage is in select markets only.

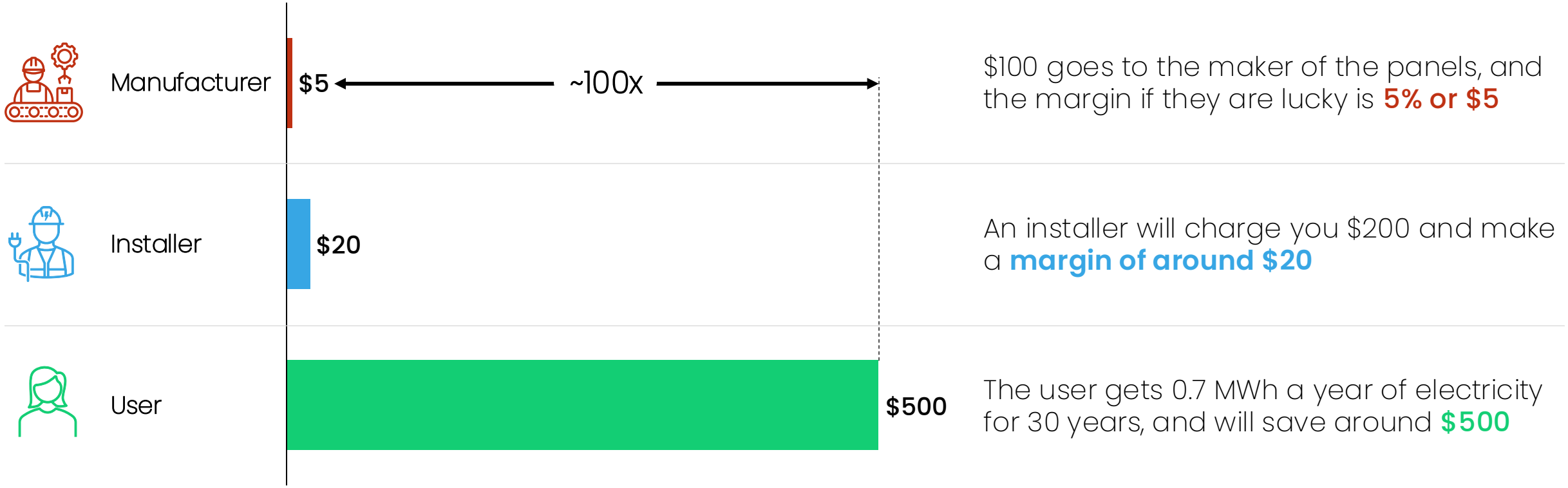
EMBER

It’s not all about manufacturing

The user benefits are 100x greater than the manufacturer profits

The economics of putting up a couple of solar panels with 1kWp of capacity, UK example

Profits



$100 goes to the maker of the panels, and the margin if they are lucky is **5% or $5**

An installer will charge you $200 and make a **margin of around $20**

The user gets 0.7 MWh a year of electricity for 30 years, and will save around **$500**

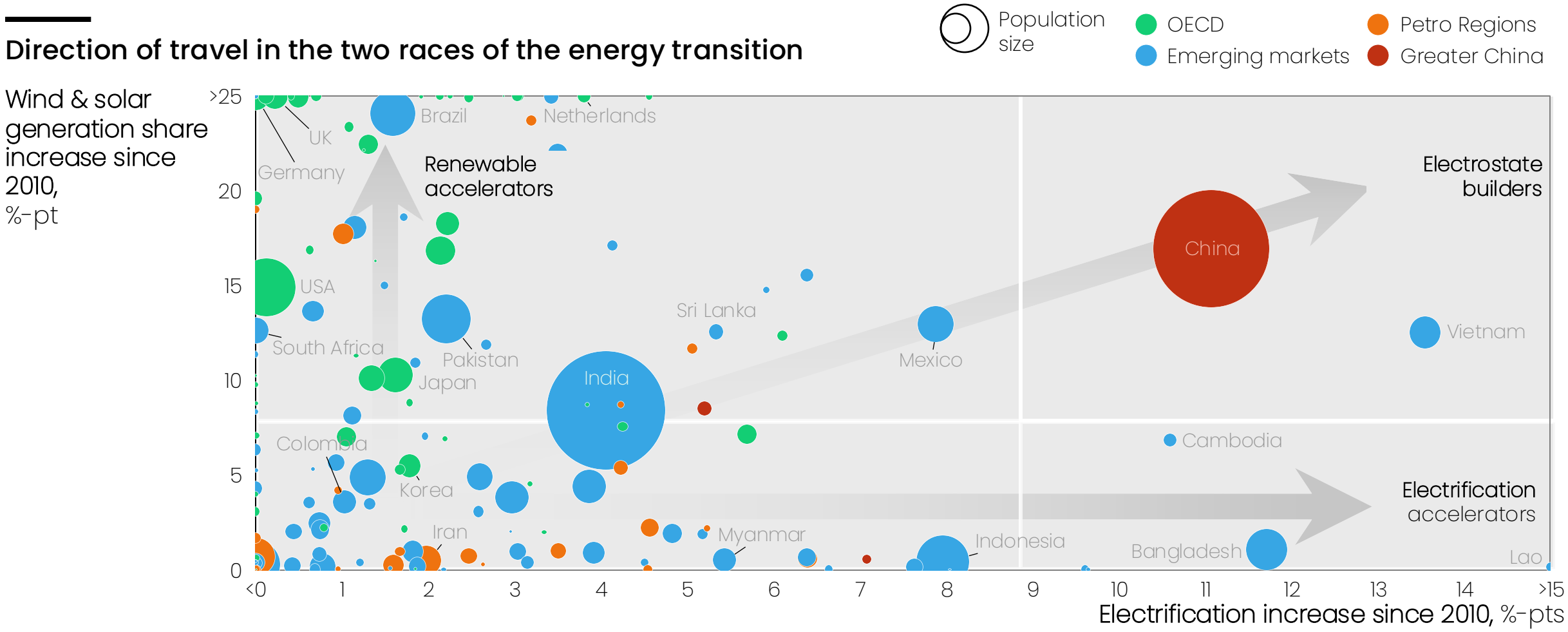
Sources: Alibaba for solar panel costs, Greenmatch for installation costs, NPV calculation for the net savings made by a retail consumer based on data from the Renewable Energy Hub and at a 7% cost of capital.

EMBER

The electrification imperative

Many countries are building renewables; few an electrostate

Direction of travel in the two races of the energy transition



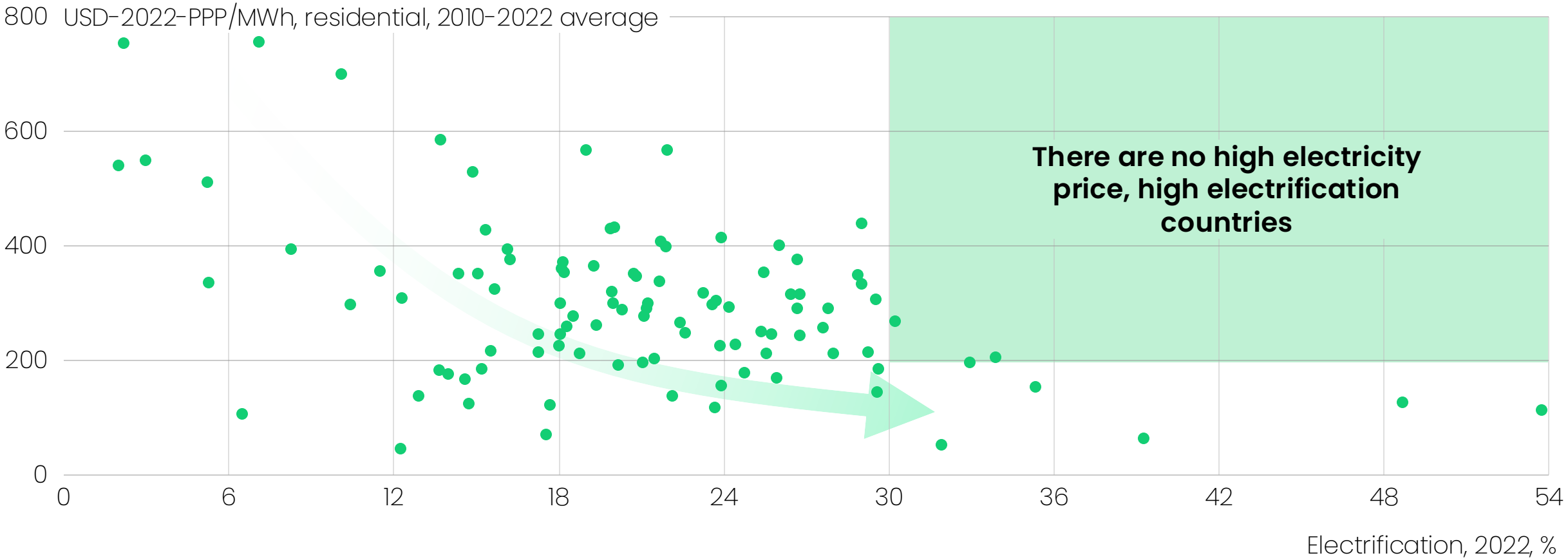
Sources: IEA WEB; Ember; Ember analysis • Note: Shown values cut off at 0-25% for wind & solar and 0-15% for electrification rates

EMBER

Econ 101

Lower prices incentivise uptake

Electricity price



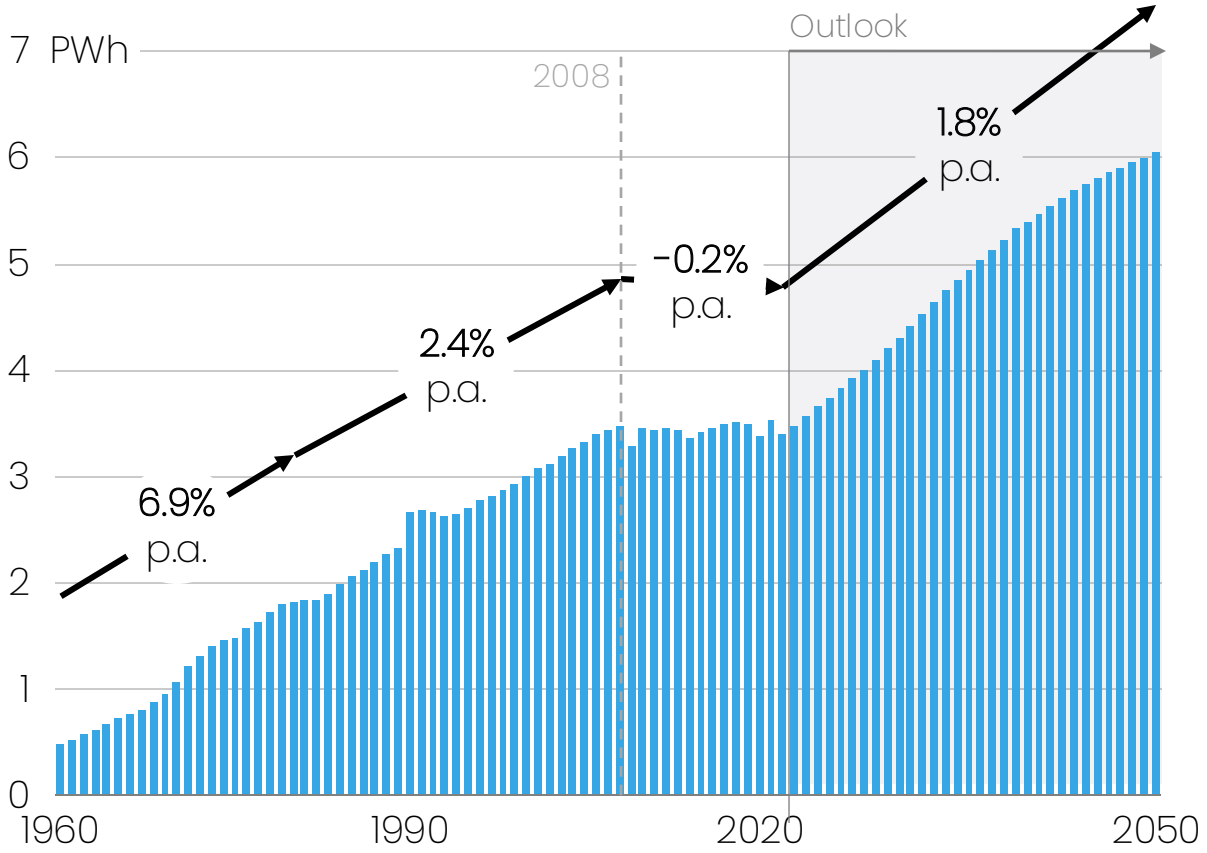
Sources: IEA; Ember analysis

EMBER

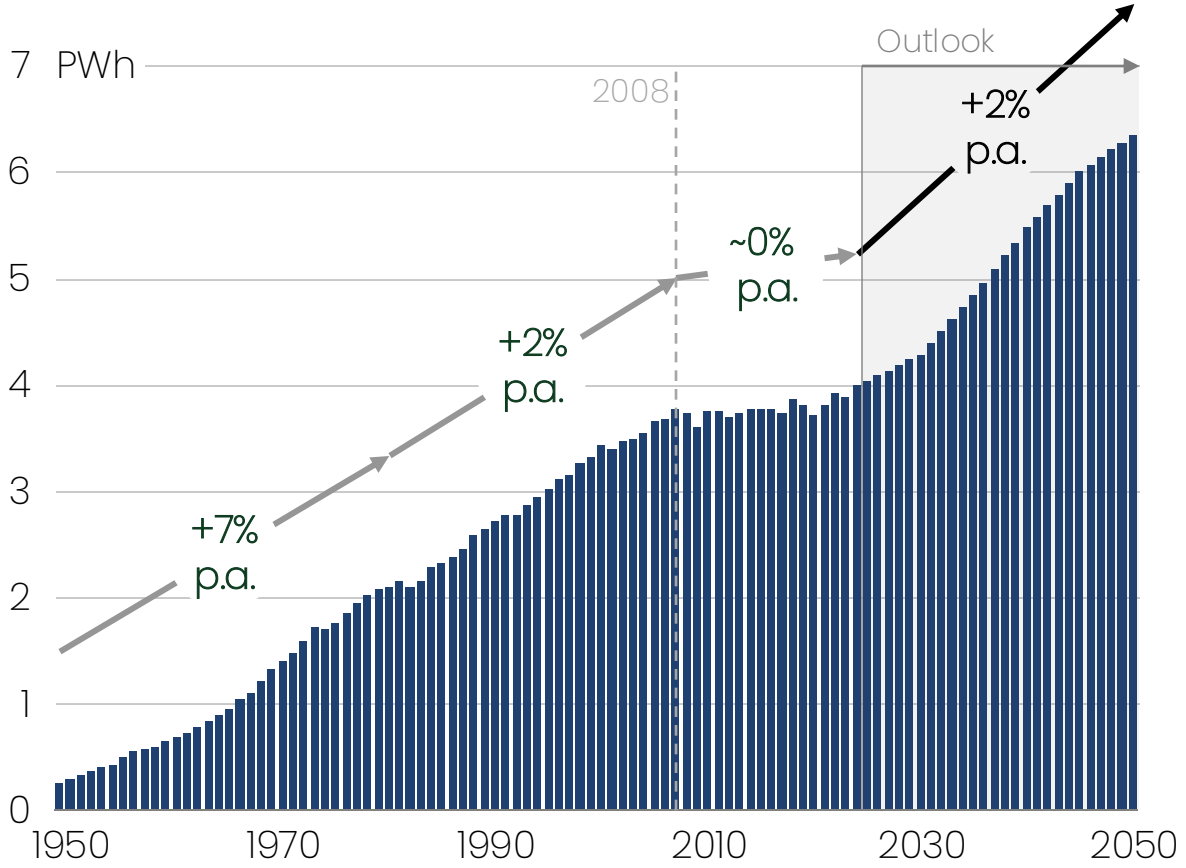
The West can get back on track with electrification

Europe and the US were able to grow electricity demand rapidly for decades before 2008

Europe electricity demand



US electricity demand



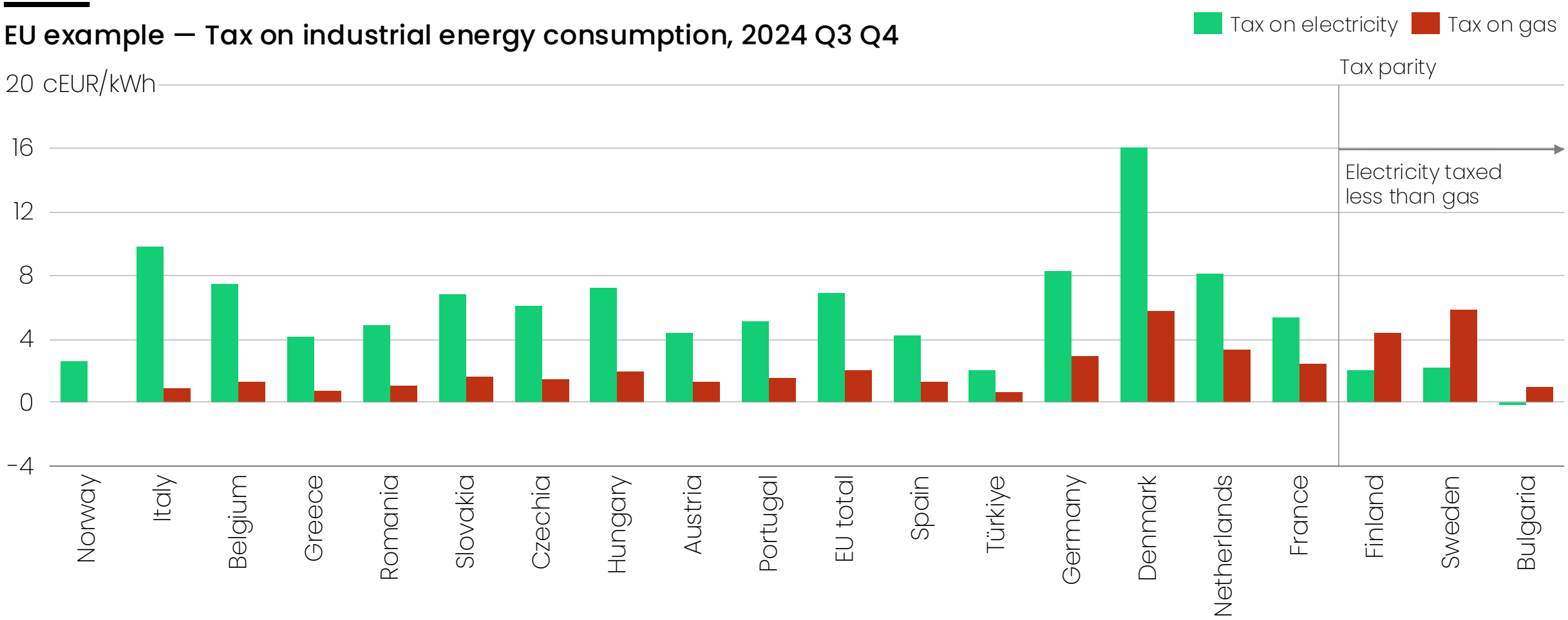
Sources: IEA WEB; IEA APS; Ember analysis

EMBER

Tax what you want to phase out

High taxes on electricity will only slow down electrification

EU example — Tax on industrial energy consumption, 2024 Q3 Q4



Sources: Eurostat; Ember analysis — based on mid-sized industrial consumer

EMBER

Experiment with policy and regulation

Just as we experiment with new tech, we should test new policies and regulations

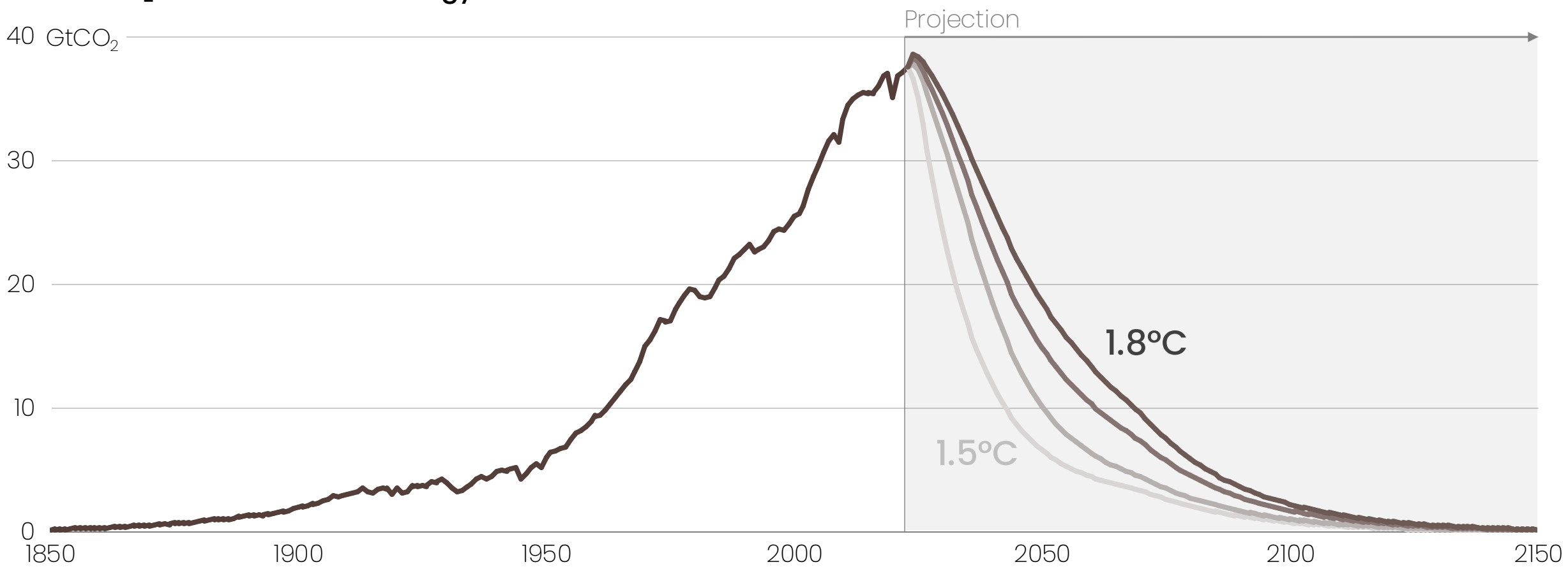
New electrotech	Different tech specs versus fossil incumbent	Example policies and regulations to experiment with to better match new tech		
Utility-scale wind & solar	Variable with weather; available everywhere; zero marginal cost	Regional pricing	Nodal/local battery tenders	Power price-setting reform
Rooftop solar & microgrids	Consumers become prosumers; power flows two ways	Connection fast tracking	Locational tariffs	Microgrid resilience payments
EVs and heat pumps	Loads get more local, mobile, and can be flexed sub-hourly; availability varies by user behavior and season	TOU and availability pricing	Storage buffer incentives	Interoperability / API sandbox
Industry electrification	Very large, shiftable electricity demand for some sites; hard baseload for other sites	Zonal demand tenders	Flexible industrial contracts	CfD for offtake prices
Grid upgrades & advanced sensing	New sensors and controls give fast, local visibility and automated options	Dynamic line rating	Performance-based payments	Private power lines

Sources: Systemiq analysis for the ETC; Ember

Falling emissions are a consequence of the Electrotech Revolution

The faster electrotech grows, the faster emissions will fall

Global CO_2 emissions from energy



Sources: Global Carbon Project, OWID (1850-2023), Rystad Energy to 2023-2070; RMI illustrative onwards.

EMBER

The time is now

01

For the first time in history, we can harness the exceptional power of the sun through electrotech

02

After a century of evolution, electrotech is now coming together in a decade of revolution; surging globally, replacing fossil fuels, and powering emerging economies

03

Change is driven by the fundamental forces of of physics, economics and geopolitics, not just climate action

04

This revolution will come faster and go further than most think, stranding more than just energy assets, and reshaping global leadership

05

This is the decisive decade. Surf the electrotech wave or be dragged under

EMBER

About Ember

Ember is an independent energy think tank that aims to accelerate the clean energy transition with data and policy. Its vision is a world with a safe climate, powered by a clean, electrified energy system for all.

About Ember Futures

This report is the first annual pitch deck from Ember Futures, a new research initiative established to help leaders navigate the rapid rise of electrotech and the decline of fossil fuels, and what this transition means for energy, financial markets, and geopolitics.

Acknowledgements

Data visualisation: Chelsea Bruce-Lockhart, Reynaldo Dizon.
Data: Sam Hawkins, Euan Graham, Nicolas Fulghum.
Strategy: Phil MacDonald, Harry Benham, Bryony Worthingon, Dave Jones, Kostantsa Rangelova, Richard Black.
Communications: Hannah Broadbent, Ardhi Arsala Rahmani, Rashmi Mishra, Rini Sucahyo.
Asia team: Aditya Lolla, Muyi Yang, Dinita Setyawati, Ruchita Shah.

With thanks to: Arthur Downing, Assaad Razzouk, Amory Lovins, Bill McKibben, Bruce Douglas, Chris Goodall, Freya Newman, Greg De Temmerman, Hannah Ritchie, Hauke Engel, Jon Hansen, Jules Kortenhorst, Kate Bassett, Leonardo Buizza, Liza Rubinstein, Mark Campanale, Maria Pastukhova, Michael Collins, Michael Seckler, Mike Hemsley, Nigel Topping, Paul Dickinson, Tom Steyer.

Cover image: NanoStockk, Getty images

Authors

Daan Walter
Sam Butler-Sloss
Kingsmill Bond, CFA

EMBER